FB. 12

AD

ADA029415

AMMRC CTR 76-22

EFFECT OF CRYSTALLOGRAPHIC TEXTURE, RETAINED AUSTENITE, AND AUSTENITE GRAIN SIZE ON THE MECHANICAL AND BALLISTIC PROPERTIES OF STEEL ARMOR PLATES

July 1976

By Hsun Hu, G. R. Speich and R. L. Miller

United States Steel Corporation
Research Laboratory
Monroeville, Pennsylvania 15146

Final Technical Report
Contract Number DAAG46-75-C-0094

Approved for public release; distribution unlimited.

Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

AMMRC CTR 76-22

EFFECT OF CRYSTALLOGRAPHIC TEXTURE, RETAINED AUSTENITE, AND AUSTENITE GRAIN SIZE ON THE MECHANICAL AND BALLISTIC PROPERTIES OF STEEL ARMOR PLATES

July 1976

By Hsun Hu, G. R. Speich and R. L. Miller

United States Steel Corporation
Research Laboratory
Monroeville, Pennsylvania 15146

Final Technical Report
Contract Number DAAG46-75-C-0094

Approved for public release; distribution unlimited.

Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

Table of Contents

FOREWORD

This report was prepared by the Research Laboratory of United States Steel Corporation under U. S. Army Contract No. DAAG-75-C-0094. The contract was administered by the U. S. Army Materials and Mechanics Research Center, Watertown, Massachusetts. This is a final report and covers work conducted from July 1, 1975 to June 30, 1976.

List of Tables

List of Illustrations

List of Illustration (continued)

Effect of Crystallographic Texture, Retained Austenite, and Austenite Grain Size on the Mechanical and Ballistic Properties of Steel Armor Plates

by

Hsun Hu, G. R. Speich, and R. L. Miller

Abstract

The ballistic performance of a medium-carbon 5Ni-Si-Cu-Mo-V steel processed to plates with various degrees of textures, various amounts of retained austenite, and various austenite grain sizes has been studied. Results show that, with 0.50 caliber projectiles and 0 degree obliquity, the V_{50} ballistic limit of nearly random-textured plates is around 2030 to 2100 fps (666 to 689 mps), at a hardness of about 53.5 to 54.5 R_C. For approximately the same hardness and in-plane mechanical properties, the ballistic limit of strongly (112) + (111) textured plates increased with increasing texture intensity. A ballistic limit of about 2360 fps (774 mps) was observed for the strongest texture produced in plates rolled 80 to 90 percent at 1500°F (815°C) before quenching. With this increased ballistic limit, the tendency for spalling also increased. At a constant strain rate, the spalling resistance appears to correlate qualitatively with the through-thickness notched tensile strength. Tempering quenched plates with a random texture at various high temperatures (1100 to 1300°F or 593 to 704°C) to vary the retained-austenite contents greatly reduced the ballistic limit, primarily because of the lowered hardness. For this range of low hardness and low ballistic limit, the latter increased with increasing retained-austenite contents, but with decreasing hardness. There was little difference in the ballistic limit of random-textured plates heat-treated to various austenite grain sizes prior to quenching. The ballistic properties of the plates and their correlations with texture, microstructure, and the through-thickness notched tensile properties are discussed.

Introduction

Results of an earlier investigation[1)*] indicated that the ballistic properties of an armor steel containing approximately 0.4C, 5Ni, 1Si, 1Cu, 0.5Mo, and 0.10V in weight percent varied with the temperature of hot rolling. Optimum ballistic performance was obtained by rolling at temperatures just above the critical range (1500°F or 815°C), followed by quenching and tempering. The observed improvement in ballistic properties was attributable to several metallurgical factors that could not be isolated individually. These included a finer martensite plate size, an increase in the content of retained austenite, and a crystallographic texture that contained an appreciable amount of (112) + (111), with little (100) orientation in the plane of the plate. All these factors could have contributed to the improvement of the ballistic properties, and it was not possible to evaluate their individual merits on the basis of the experimental results obtained.

The main purpose of the present investigation was to determine the relative importance of three variables—1) preferred orientation, 2) retained austenite, and 3) prior austenite grain size—on the ballistic properties of quenched and tempered armor steel plates. To this end, it was imperative that for each of these variables, the effects of the others be minimized or kept constant. For the study of the effect of preferred orientation,

---

* See References.

it was also important that textures of considerably stronger intensities than those obtained previously[1] be produced. Preferably, several kinds of textures should be produced, each with various degrees in intensity, so that the effects on ballistic properties of different preferred orientations, and different intensities of each preferred orientation, could be compared and correlated.

The present investigation was conducted under Research Contract No. DAAG46-75-C-0094 awarded by the Army Materials and Mechanics Research Center (AMMRC) to the United States Steel Corporation on July 1, 1975.

Materials and Procedures

Steel Composition and Ingot Dimensions

Two 500-lb (227 kg) heats, of nominally the same chemical compositon as that of the steel used previously,[1] were vacuum-melted and cast at the Laboratory. Both ingots were 7 by 12 by 24 inches (180 by 300 by 600 mm) in dimension, one intended for the study of the effects of texture, and the other for the study of the effects of retained austenite and of prior austenite grain size on the ballistic properties of quenched and tempered plates. Check analyses of samples taken from the hot-rolled plates, 0.75-inch (19 mm) thick (Ingot A) and 0.55-inch (14 mm) thick (Ingot B) are shown in Table I. These compositions matched closely with those of earlier steels.[1]

Hot-Rolling Procedures

Because of the practical difficulty of conducting a homogenizing treatment in the laboratory, no special homogenizing anneal was given to the ingots or the slabs. The ingots were soaked at 2250°F (1230°C) for two hours and then hot-rolled to an intermediate thickness. The complete hot-rolling procedures were as follows:

Material for Retained-Austenite and Austenite-Grain-Size Studies (Ingot A). The ingot was hot-rolled from 7 to 4 inches (180 to 100 mm) thick, cooled in air, and cut into three pieces of approximately equal length. The three 4-inch-thick slabs were reheated to 2100°F (1150°C) in two hours, cross-rolled to 2-1/8 inches (54 mm) thick, and air-cooled. After the edges were trimmed, each plate was again cut in length, providing two equal pieces. These 2-1/8-inch-thick plates were reheated to 2100°F, and straight-rolled to a final thickness of 0.75 inch (19 mm). Samples from this material were used for various heat treatments and studies. For ballistic tests after various final heat treatments, full-size plates, 6 by 12 inches (150 by 300 mm) in dimension, were provided by this material.

As can be noted from these hot-rolling procedures (such as heating to 2100°F for each step in the rolling sequence, cross rolling, conducting only a moderate amount of reduction between reheatings, etc.), the purpose of the procedures was to avoid

introducing preferred orientations in the material. A final reaustenitizing treatment of the plate further randomized the texture of the plates so that the study of the effect of retained austenite and of austenite grain size on the ballistic properties of the plates was isolated from the effect of textures.

Material for Texture Studies (Ingot B). In contrast to the procedures employed for Ingot A, the hot-rolling procedures applied to Ingot B were intended to develop textures with high degrees of intensity or sharpness by increasing the amount of reduction at an appropriate temperature. The ingot was hot-rolled from 7 inches to various intermediate thicknesses, namely 5.50, 2.75, 1.85, and 1.40 inches (140, 70, 47, and 36 mm). During this hot rolling, a piece was torch-cut successively from the tail end of the slab when the desired thickness was reached.* Each of these intermediate pieces, after cooling in air, was cut into two pieces by abrasive sawing along the midwidth line. Thus, duplicate pieces were obtained at each intermediate thickness, providing two identical sets of material for final processing. A small hole was drilled in each of these pieces by electrical discharge machining (EDM) at approximately the midposition of thickness and width. During final rolling, a thermocouple was inserted into this hole for temperature monitoring.

---

* By such a sequence of torch cutting the thickest intermediate piece (5.50 in. thick, to be finally rolled to 90% reduction in thickness) corresponded to the top end of the ingot, since in hot rolling the bottom end of the ingot entered the rolling mill first.

One set of the intermediate material was processed by reheating to 1700°F (925°C), isothermal rolling at 1500°F (815°C) to a final thickness of 0.55 inch (14 mm), and water-spray quenching to room temperature. This procedure resulted in reductions in thickness of 60 to 90 percent for the intermediate pieces 1.40 to 5.50 inches thick. Isothermal conditions were closely approximated in rolling the 1.40- and 1.85-inch-thick pieces; no difficulty was encountered in cooling the piece from the reheating temperature of 1700°F to the desired isothermal temperature of 1500°F before starting to roll. The amount of reduction in a pass was so adjusted that the heat lost by radiation or convection was nearly balanced by the heat generated during deformation. For the more massive pieces (2.75 and 5.50 inches thick), it was necessary to start rolling at a somewhat higher temperature than the desired isothermal temperature of 1500°F (around 1575 and 1600°F, as indicated by the inserted thermocouple). Otherwise, the corners and edges of the piece would be cooled excessively in comparison with the interior. However, such deviations in the desired conditions were corrected after the first few passes. The difficulties resulting from cool corners and edges could, of course, be easily avoided by using a second furnace set at the desired temperature for rolling.

The microstructure, preferred orientation, and mechanical and ballistic properties of this set of plates were studied after

a tempering treatment of 1 hour at 350°F (177°C) was given to the material that had been hot-rolled and water-quenched on the mill. Various preliminary experiments were conducted to study the textural behavior of the present armor steel, so that the possibility of producing full-size plates with various kinds of textures for later ballistic-performance studies could be developed. The second set of intermediate pieces was reserved for this purpose. The thermo-mechanical processing details for the second set of pieces will be described later in this report.

Experimental Results

The Critical Range of the Armor Steel

To ensure that the transformation characteristics of the steel made for the present investigation were essentially equivalent to those of the steels used earlier,[1)] the critical range of the steel was determined by the same techniques used in the earlier studies. Small specimens cut from the rolled plates (Ingot A) were austenitized at 1650°F (900°C) for one hour, quenched, and heated for one hour at various temperatures ranging from 950 to 1400°F (510 to 760°C), followed by quenching in water (75°F or 24°C), or in liquid nitrogen (-320°F or -196°C). The changes in hardness and in the amount of retained austenite as a function of the heating temperature are shown in Figure 1.

Results from the present water-quenched specimens were in good agreement with those obtained earlier. The volume fraction of

retained austenite was about 4.5 percent at 1050 to 1075°F (565 to 580°C), then it began to increase with the heating temperature and reached a maximum (20.5%) at 1250°F (675°C). The austenite content then decreased to about the same low initial value (4.4%) at 1350°F (732°C) where the hardness was a maximum. Quenching in liquid nitrogen markedly reduced the maximum content of retained austenite in specimens heated at 1200 and 1250°F (650 and 675°C).

Temperature Dependence of the Austenite Grain Size

To provide general information on the size of the austenite grains in austenitizing treatments, and a frame of reference for studying the effect of prior austenite grain size on the properties of quenched and tempered armor plates, the austenite grain size as a function of austenitizing temperature was determined. Small specimens were austenitized for one hour at various temperatures ranging from 1500 to 2300°F (815 to 1260°C) and quenched in water. The average diameter of the prior austenite grains was determined metallographically both on the rolling plane and on longitudinal sections.

The results are shown in Figure 2. As can be noted, grain growth of the austenite of the armor steel was negligible up to 1900°F (1038°C). At austenitizing temperatures higher than 2100°F (1150°C), exaggerated growth or grain coarsening occurred precipitously. These features are characteristic of grain-growth inhibition by finely dispersed second-phase particles. The austenite

grains were equiaxed after austenitizing at the high temperatures, but less so at the low temperatures. The hardness and the retained-austenite contents varied very little with the austenitizing temperatures, ranging from 52.5 to 55.0 R_C and from 6.2 to 7.5 percent, respectively.

Textural Behavior of the Armor Steel

The textural behavior of the armor steel was investigated extensively in a number of experiments with small specimens, using X-ray diffraction. Both the (110) and (200) pole figures were determined with a ZrO_2-filtered MoK_α radiation and the reflection technique. From the center of projection which corresponds to the normal of the rolling plane, the pole figures were plotted to a tilting angle of 80 degrees. The temperature limits in the austenite region for rolling reductions up to 90 percent without concurrent recrystallization or ferrite formation were found to be around 1600 and 1300°F (870 and 700°C), respectively. Within this range of temperatures for isothermal rolling, the effect of the initial heating temperature (in the range 1350 to 2100°F or 730 to 1150°C), and the effect of the post rolling annealing temperature for recrystallization of the austenite (in the range 1650 to 2000°F or 900 to 1093°C), on the nature and the degree of texture of the martensite were investigated extensively.

Results of these experiments indicated that isothermal rolling within the temperature range 1300 to 1600°F develops the

copper-type rolling texture. Annealing at a higher temperature immediately after rolling recrystallizes the austenite, and changes the texture to cube orientation. The sharpness of the cube texture of recrystallized austenite (as deduced from the sharpness of the texture of quenched martensite) will be affected by the reheating temperature, the amount of isothermal rolling reduction, and the temperature of the recrystallization anneal in a way that is completely consistent with the principles of rolling and annealing texture formation in fcc metals of high stacking-fault energies.[2-4)]

Because the nature and the intensity of the texture of martensite depend entirely on those of the parent-phase austenite, the texture of quenched armor-steel plates can be controlled only by appropriate thermomechanical processing treatments of the steel in the austenite region. Results obtained from these experiments indicated that at least two different kinds of textures, each with variable degrees of intensity, could be produced by controlled thermomechanical processing treatments prior to quenching. Reaustenitizing and quenching of the textured martensite tends to produce a weakened texture, frequently of a different kind. This may provide additional information concerning the effect of texture on the mechanical properties and ballistic performance of armor-steel plates.

Texture of Martensite Produced by
Quenching Deformed Austenite

The textures of the 0.55-inch-thick plates, isothermally rolled 60 to 90 percent at 1500°F (815°C), then quenched and tempered, were examined by determining (110) and (200) pole figures at 3/4-thickness (that is, quarterthickness below the surface) and midthickness sections. The nature of the texture was very similar at both sections, but the texture at the midthickness was sharper and stronger. Figures 3A to 3D show the (110) pole figures determined from the midthickness section of the plates rolled 90 to 60 percent, respectively. The corresponding (200) pole figures are shown in Figures 4A to 4D. The textures can be described as mainly of $(112)[1\bar{1}0]$ + $(111)[\bar{1}\bar{1}2]$ orientations, in agreement with previous observations,[1)] and with the textures reported by others[5,6)] for hot-rolled and quenched steels of different chemical compositions. As can be noted from these pole figures, the texture intensity increased with rolling reduction. Taking the average intensity maxima in the (110) pole figures (Figures 3A to 3D) as an indicator, the texture intensity increased from 3.75 for the plate rolled 60 percent to 6.50 for the plate rolled 90 percent.

Using materials of smaller thicknesses (0.5 to 1.0 inch or 13 to 25 mm), reheating and isothermal rolling at 1350°F (732°C) to a final thickness of 0.20 and 0.10 inch (5.1 and 2.5 mm) after 80 and 90 percent reductions produced essentially the same textures as shown in Figures 3A and 3D.

Texture of Martensite Produced by Quenching Recrystallized Austenite

Similar studies were made of the textures in thin specimens (0.10 to 0.20 inch thick) rolled 60 to 90 percent at 1350°F and immediately annealed at 1800°F for recrystallization, then quenched. In contrast to the textures produced by quenching the deformed austenite, which were in fact fairly complex (see pole figures in Figures 3 and 4), the martensite produced by quenching the recrystallized austenite had a rather simple texture, Figures 5A to 5D. The simplicity of the texture was strikingly shown by the specimen that was rolled to a high reduction. The nature of the texture, as can be identified more readily by the strongest texture shown in Figure 5A, may be described as approximately (110)[001].* The intensity of the texture decreased with decreasing rolling reduction, from 2.80 in the specimen rolled 90 percent to 1.20 in the specimen rolled 60 percent, based on the average intensity maxima in the (110) pole figures. As a matter of fact, the texture intensity of the specimen rolled 60 percent was so weak that it could hardly be described as being of a specific preferred orientation (see Figure 5D).

The results of these experiments were used as a basis for processing the remaining set of the intermediate material, having thicknesses of 1.40, 1.85, 2.75, and 5.50 inches to full-size

---

* Based on the (200) figure shown, for example, in Figure 6B, the texture should contain another prominent component of the (110[$\bar{1}$10] orientation.

ballistic plates by quenching the recrystallized austenite. However, in the processing of these full-size plates, the start-rolling temperature had to be raised appreciably to ensure that the hot-rolled pieces could be recharged into the furnace for annealing for recrystallization* before any phase transformation could occur because of falling temperatures. The intermediate pieces were reheated to 1800°F (980°C). For the 1.40- and 1.85-inch-thick pieces, hot rolling started at 1600°F (870°C) and continued to reductions of 60 and 70 percent, respectively, with the temperature falling from 1600 to 1500°F (870 to 815°C). The pieces were recharged into the furnace at 1800°F, held for 30 minutes to effect recrystallization, and then quenched by water spray to room temperature.

For the 2.75- and 5.50-inch-thick pieces, hot rolling started at 1700°F (926°C) and continued to reductions of 80 and 90 percent, respectively, with the temperature falling from 1700 to 1500°F. The pieces were recharged into the furnace at 1800°F, held for 30 minutes to effect recrystallization, and finally water-spray-quenched to room temperature. As a consequence of the considerably higher start-rolling temperatures, concurrent recrystallization must have occurred during the early rolling passes. As a result, the rolling textures were less strongly developed than

---

* For the pieces to be rolled to 80 and 90 percent reductions, the material had to be torch-cut at an appropriately reduced thickness to decrease its length during the hot-rolling process so that the shortened pieces could be recharged into the furnace for recrystallization anneal after finish rolling.

those obtained with isothermal rolling at a lower temperature. Accordingly, the cube texture of the recrystallized austenite was weakened; as a result, a weakened martensite texture was obtained.

The textures of the full-size ballistic plates, processed by quenching the recrystallized austenite as described above, were examined. Figures 6A and 6B are the (110) and (200) pole figures, respectively, of the plate rolled 90 percent. On the basis of the (200) pole figure, the texture should be described as (110)[001] + (110)[$\bar{1}$10]. In comparison with the texture observed in the small specimen rolled to the same reduction (Figure 5A), the intensity of the (110) texture of the full-size plate was substantially weaker (compare Figure 6A with Figure 5A). In fact, the whole range of texture intensity developed in these full-size ballistic plates was not significantly higher than random. This unfortunate outcome was clearly due to experimental limitations. Arrangements to facilitate the reannealing of the rolled plates for recrystallization before any phase transformation occurs would remove such difficulties.

Texture of the Martensite Produced by Reaustenitizing and Quenching

As a supplement to the above investigations, the effect of reaustenitizing and quenching a textured martensite on the final texture of the plate was also examined. Since reaustenitizing and quenching treatments will change the texture of the martensite to a different kind (although with a weaker intensity), results

from such experiments may provide additional information concerning the effect of texture on the ballistic properties of the armor-steel plates. For this purpose, some of the plates produced by quenching the deformed austenite and by quenching the recrystallized austenite were reaustenitized at 1800°F (980°C) and quenched. After tempering at 350°F (177°C) for 1 hour, the textures of the specimens were examined.

Based on the (110) and (200) pole figures, the texture of the plate initially rolled 90 percent and quenched from the deformed austenite contained a relatively prominent (110) component in the plane of the plate. For the plate initially rolled 90 percent and quenched from the recrystallized austenite, reaustenitizing and quenching treatments produced a prominent (113) component in the plane of the plate. The intensity of these textures decreased with decreasing initial hot-rolling reduction, or with weaker initial texture intensity of the martensite. In fact, for the plates initially rolled to 70 and 60 percent reductions, the reaustenitizing and quenching treatments practically randomized the textures. The (110) pole figures shown in Figure 7 (for the plate initially rolled 90 percent and quenched from deformed austenite), and Figure 8 (for the plate initially rolled 90 percent and quenched from recrystallized austenite) represent the strongest textures observed among these groups of specimens.

Texture of Plates for Retained-Austenite and Austenite-Grain-Size Studies

As mentioned earlier, the effects of retained austenite and of prior austenite grain size on the ballistic properties of quenched and tempered armor-steel plates were to be studied free from any influence of textures. The textures of the plates, after austenitizing at several temperatures and quenching, were examined by the X-ray peak intensity measurements of various reflections. The results are shown in Table II. Except for the slight indication that a weak surface texture appeared to have been developed in the specimen austenitized at 2300°F (1260°C) [as shown by the somewhat higher (200) and (222), but lower (211) intensities], the textures of the specimens were practically random through the thickness of the plates. The very weak surface texture shown by the specimen austenitized at 2300°F was undoubtedly due to grain growth and surface decarburization that had occurred at this high temperature.

Mechanical Properties of the Plates

Influence of Texture. For textured plates, tension-test specimens 0.25 inch (6.3 mm) in diameter were prepared from the quenched and tempered (1 hr at 350°F or 177°C) steel and tested along both the longitudinal and the transverse directions. For random-textured plates, only the longitudinal specimens were tested, and the transverse properties were not expected to be significantly different.

Table III summarizes the tensile properties of the plates processed by quenching the deformed austenite. These plates, as shown previously by the pole figures in Figures 3 and 4, were strongly textured, having mainly (112) + (111) orientations in the plane of the plate, and decreased texture intensities at lower rolling reductions. The strength and ductility of the plates varied only insignificantly as a function of either rolling reduction or degree of texture. However, there was a marked anisotropy in strength and ductility, which increased with rolling reduction. This is clearly indicated by the differences in properties between the specimens tested in the longitudinal and the transverse directions.

The tensile properties of plates processed by quenching the recrystallized austenite are shown in Table IV. The yield strength increased slightly with increasing rolling reduction, whereas the tensile strength, reduction in area, and total elongation varied very little among the plates. There was much less anisotropy in comparison with the plates processed by quenching the deformed austenite (Table III). This can readily be explained on the basis that a cube-textured austenite, hence its transformation products, would display nearly the same properties in both the longitudinal and transverse directions, because they are crystallographically equivalent. Also, the texture of the martensite in the full-size plates produced by quenching the recrystallized austenite was substantially weakened because experimental difficulties resulted in less-than-optimum hot-rolling conditions.

The tensile properties of armor-steel plates processed by reaustenitizing and quenching textured martensite are shown in Table V. Since the textures of these plates were nearly random, except for those plates that were rolled 90 percent and had a weak texture, there was very little difference in yield or tensile strength between the longitudinal and the transverse directions. The yield strength of the plates rolled 90 percent appeared to be slightly lower, and the ductility slightly higher, than those of the plates rolled only 70 percent. The reduction in area was appreciably higher in the longitudinal direction than in the transverse direction of these plates. However, anisotropy in reduction of area is highly sensitive to the morphology and distribution of inclusions. The reaustenitizing treatment would only influence such factors as grain shape, dislocation distribution, and texture. Accordingly, the reduction in anisotropy observed (compare Table V with Tables III and IV) results from randomizing these latter factors by reaustenitizing.

Influence of Retained Austenite. The tensile properties of armor steel plates heat-treated to various retained-austenite contents and tempered 1 hour at 350°F are shown in Table VI. As would be expected, the yield strength decreased with increasing retained austenite. The change in tensile strength and ductility showed little correlation with the retained austenite, even though the change in elongation followed the general trend of the retained-

austenite changes. The yield-to-tensile strength ratio decreased with increasing tempering temperature within the temperature range studied.

Influence of Austenite Grain Size. Specimens austenitized at various temperatures, quenched in water, and tempered 1 hour at 350°F were tested for their tensile properties as a function of prior austenite grain size. The results are shown in Table VII. Except for the specimen austenitized at 2300°F, in which quench cracks developed, a tendency for a slightly decreased yield strength with increasing prior austenite grain size was indicated. The tensile strength and elongation varied insignificantly. Quenching stresses in these specimens, which depend on the temperature and on the size of the specimen, make such correlations difficult. Standard longitudinal Charpy V-notch impact tests at 75°F on these specimens showed that the notch toughness varied within narrow limits of 15 to 17 ft-lb (20 to 23 J).

Ballistic Performance of the Plates

Full-size ballistic-test plates processed by the various thermomechanical treatments to produce various kinds and degrees of texture, various amounts of retained austenite, and various sizes of the prior austenite grains were final-tempered at 350°F for 1 hour, ground on both surfaces to remove oxide scale and decarburized

layer, and tested for the V_{50} ballistic limit* with 0.50 caliber projectiles at 0 degree obliquity. The results are summarized as follows.

Effect of Texture. The ballistic performance of the plates processed by quenching the deformed austenite to produce a strong (112) + (111) texture, together with the texture data and other physical or structural features, are shown in Table VIII. These results indicate that the ballistic limits increased with increasing hot-rolling reduction, or with texture intensity, at approximately the same hardness and retained-austenite content. It was shown earlier that the strength and other mechanical properties of these plates were nearly the same (Table III).

Data for the plates processed by quenching recrystallized austenite are shown in Table IX. The ballistic limits of all the plates were about the same, as were their hardness and retained-austenite contents. The texture of the plates ranged from weak (110) to nearly random. For all practical purposes, the texture of all these plates could be considered as virtually random. Accordingly, the ballistic limits showed very little difference among the plates.

---

* The V_{50} ballistic limit (protection ballistic limit) is defined as the velocity of the projectile at which the armor plate has a 50 percent probability to be penetrated by the projectile, penetration being defined as puncture of an aluminum witness sheet 6 inches behind the target.

Plates processed by reaustenitizing and quenching, Table X, showed approximately the same ballistic limits as plates processed by quenching recrystallized austenite. Because of the low texture intensities of the reaustenitized and quenched plates, the results shown in Table X, particularly those for plates with relatively low rolling reductions, could be considered as data from random-textured specimens. The retained-austenite content was somewhat higher in these plates than in those processed by quenching deformed austenite (Table VIII). The hardness was nearly the same for all the plates tested. However, the ballistic limits of these nearly random-textured plates were substantially lower than those of plates having strongly (112) + (111) textures (Table VIII).

Effect of Retained Austenite. The ballistic performance and other features of the plates, as influenced by the amount of retained austenite, are shown in Table XI and Figure 9. As the results indicated, the ballistic limits of the plates tempered at high temperatures (1100 to 1300°F or 593 to 704°C) were all very low, as were their hardnesses. It is known that for high-hardness steel targets, the ballistic limit increases with increasing hardness or tensile strength.[7)] The ballistic properties of these relatively low-hardness plates with random texture showed improvements with increasing retained austenite even though the hardness was decreasing when the plates were tempered at 1100 to 1200°F (593 to 650°C). Upon tempering at still higher temperatures (from 1200 to 1300°F),

the ballistic limit decreased with decreasing amounts of retained austenite, whereas the hardness of the plate increased. These interesting observations may be related to increased work-hardening and toughness improvement generally associated with this type of retained austenite. Additional cryogenic treatment (by immersing a quenched specimen in liquid nitrogen for 30 minutes) of a specimen tempered at 1250°F further reduced the content of retained austenite and reduced the ballistic limit, even though there was a slight increase in hardness.

Effect of Austenite Grain Size. The ballistic limits of the plates heat-treated to various austenite grain sizes before quenching are shown in Table XII. It can be seen that the ballistic performance of these random-textured plates was not significantly affected by the prior austenite grain size. The similarity in hardness, yield and tensile strength, retained austenite, and the ballistic limits of the plates shown in Tables IV, IX, and X with those in Tables VIII and XII seems to indicate that the ballistic performance of random-textured plates was little affected by the thermomechanical history by which the random texture was produced.

Discussion

The results of the present investigation showed that the ballistic limits of strongly (112) + (111) textured plates increased significantly with increasing texture intensity, or rolling reduction, at approximately the same hardness, amount of retained austenite,

and mechanical properties (Tables III and VIII). For other kinds of textures, such as (110), (100), or (113), it was unfortunate that the intensities were not produced to sufficiently high levels to yield specific information that would be of interest regarding the effect of texture on ballistic properties. Tempering quenched plates at various high temperatures to vary the amount of retained austenite greatly reduced the ballistic limits of the plates. The ballistic limits of random-textured plates were very little affected by the prior austenite grain size. Thus, our major discussions of the present work will be centered on the increased ballistic limit with increasing texture intensity of the (112) + (111) texture.

Correlation Between Texture and Ballistic Limits

Based on the ballistic limits observed for the plates produced by quenching the deformed austenite after various rolling reduction at 1500°F (Table VIII), a correlation of the Weight Merit Rating* or the Velocity Merit Rating** with the amount of rolling reduction, hence the texture intensity, is shown in Figure 10. The merit ratings of nearly random-textured plates are also indicated. The weight merit rating, in particular, increases markedly with increasing rolling reduction, hence with the degree of texture intensity.

---

* The Weight Merit Rating is defined as the ratio of the areal density of equivalent standard homogeneous steel armor to the areal density of the experimental armor at the same V_{50} protection ballistic limit.

** The Velocity Merit Rating is defined as the ratio of the V_{50} protection ballistic limit of the experimental armor to that of the standard armor at the same plate thickness.

Because of the carefully planned processing treatment of these plates, the observed difference in their ballistic limits would have to be a consequence of their texture intensities. Since the reheating temperature for hot rolling was the same (1700°F or 927°C), the penultimate grain size of the austenite would be the same. Since the hot rolling was nearly isothermal, and was at about the same temperature for all these plates, the temperature of deformation, hence the characteristics of plastic flow and of dynamic recovery during deformation, would also be nearly the same. Thus the only significant difference among the processed plates was the amount of rolling reduction, which varied from 60 to 90 percent. Consequently, the nature of the texture of the plates was the same, only the degree of the texture intensity being different. This was already shown by the pole figures (Figures 3A to 3D and Figures 4A to 4D).

Microstructure of Textured Plates

Since the plates were rolled to various reductions and then quenched, it is possible that the fineness of the microstructure might be different. Consequently, the ballistic properties could be different, even though the conventional tensile properties were approximately the same. To clarify these possible implications, the microstructures of the plates, after tempering for 1 hour at 350°F, were examined thoroughly by light microscopy on three orthogonal sections: 1) parallel to the rolling plane, 2) longi-

tudinal cross-section, and 3) transverse cross section, and by transmission electron microscopy (TEM) on the longitudinal and transverse cross-sections.

The microstructures are shown in Figures 11A and 11B (light microscopy of the plates rolled 90 and 60 percent, respectively), and in Figure 12 (TEM of the plates rolled 90 and 60 percent). The microstructures shown in Figures 11A and 11B indicated only small differences in the thickness of the structural bands (shown more clearly in the longitudinal section). The average thickness of the structural bands lying parallel to the rolling plane was about 2.2 μm for the plate rolled 90 percent (Figure 11A). These measured thicknesses of the structural bands do not correspond to the reduced thicknesses of the austenite grains after the respective rolling reductions. The structural bands are believed to represent the various crystallographically equivalent texture components that are present in the plates. As shown by the transmission electron micrographs in Figure 12, which are representative of the specimens, there is very little difference in the plate size of the martensite, or in the frequency of microtwins, which were observed only very infrequently in the present armor steel. These microstructural features indicate that the observed difference in the ballistic limits of the plates probably did not result from a significant difference in the microstructures.

The increased resistance to ballistic penetration with increasing texture intensity of the (112) + (111) orientations is consistent with the observation that the Young's modulus in the normal direction to the plane of the plate is high,[1] because the [111] direction has the highest modulus in iron,[8] and [112] is very close to [111]. With the reflected stress-waves in the [111] direction, the cleavage planes, {100}, would also receive lower resolved stresses.

Tendency for Spalling Upon Ballistic Impact

Although the resistance to penetration increased with increasing intensity of the (112) + (111) texture, the tendency for spalling on the exit side of the plates also appeared to increase with increasing texture intensity. The photographs in Figures 13A to 13D show the front and back sides of the plates after ballistic testing. Figure 14 shows similar photographs of a random-textured plate. The ballistic limit of this plate was low, only 2031 fps (Table X). As can be seen on the back side of the plate, the penetration is sharp and the exit hole is fairly clean-cut. However, the strongly textured plates having a high ballistic limit of about 2360 fps show a strong tendency for spalling, Figures 13A and 13B (plates rolled 90 and 80 percent, respectively, prior to quenching). Even for the plate rolled 60 percent, which had a less strong texture, spalling occurred in one of the penetrations (Figure 13D). Since the tendency for spalling usually increases with the velocity

of impact, the observed effect of texture on spalling tendency may be a consequence of the improved ballistic limits of the textured plates.[9)]

According to a suggestion made by Dr. O. Richmond[10)] of U. S. Steel's Research Laboratory, the resistance to spalling at a constant strain rate might be determined for plates by testing the through-thickness tensile properties under the strain conditions that occur on spalling. That is, the principal strains in the plane of the plate $\varepsilon_1 = \varepsilon_2 \approx 0$, and the tensile strength in the thickness direction is to be tested. The 0.5-inch-thick armor plates were tempered for 1 hour at 350°F and specimens, Figure 15, were prepared by grinding. As can be noted from the dimensions of the specimens, such tests would, in fact, give the properties of the midthickness section. Since all the armor-steel plates were studied in the quenched and tempered condition, the midthickness section would probably be the least effectively cooled in quenching, hence the weakest in strength. This would be the most desirable region to test, assuming no overriding inhomogeneities exist as a result of inclusion morphology and distribution, because the plane of least resistance determines the usefulness of the plates.

Results for selectively tested specimens are shown in Table XIII. Column (1) lists the average strength of the plates with strong (112) + (111) textures tested with duplicate (for plates rolled 80 and 70 percent) or quadruplicate (for plates

rolled 90 and 60 percent) specimens. For Column (2), which shows the strength of the textured plates produced by quenching recrystallized austenite, only the two extreme specimens were tested. Columns (3) and (4) list the strengths of only the least-rolled plates, which represent the random-textured materials.

The results indicate that the through-thickness notched tensile strength decreased with increasing rolling reduction, hence with increasing texture intensity. The present finding thus appears to be qualitatively consistent with the observation that the spalling tendency of the (112) + (111) textured plates appeared to increase with increasing texture intensity. The notched tensile strength was the highest for the random-textured plates [Columns (3) or (4) in Table XIII], which is also in agreement with the practical absence of spalling in these plates (see, for example, Figure 14). The observed through-thickness notched tensile strengths were considerably higher than the in-plane tensile strengths tested in the longitudinal or transverse directions (Tables III, V, and VII) because, according to plasticity theory,[11)] the strength of a notched specimen in a ductile material like mild steel would be higher than that of a conventional specimen.

The observed decrease in spalling resistance with increasing texture intensity of the (112) + (111) orientation is believed to have arisen from the microstructural features of the textured specimen, such as the structural bands lying parallel to the plane

of the plates (Figures 11A and 11B). The degree of texture intensity itself should not influence the spalling resistance of the plates.

Summary and Conclusions

The effects of crystallographic texture, retained austenite, and austenite grain size on the mechanical and ballistic properties of high-hardness armor of a medium carbon, 5Ni-Si-Cu-Mo-V steel have been studied. For the study of the effect of textures, appropriate thermomechanical processing treatments had to be developed to produce textures of different nature, each having variable degrees of intensity. At least two different kinds of textures, each having various degrees of intensity could be produced in the high-hardness steel armor by the controlled thermal-mechanical processing procedures developed.

For the retained-austenite and austenite grain-size studies, the plates were processed to have a random texture so that influencing factors were separated. Results of the present investigation may be summarized as follows:

1. Rolling the armor steel in the austenite region without concurrent recrystallization produced a copper-type rolling texture. Quenching the deformed austenite immediately after rolling produced martensite with a strong (112) + (111) texture. By varying the amount of rolling reduction, various intensities of the (112) + (111) texture were obtained.

2. When the deformed austenite with a strong copper-type rolling texture was annealed, a strong cube texture was assumed by the recrystallized austenite. Quenching the cube-textured austenite produced martensite with a strong (110)-type texture. By varying the amount of rolling reduction, various intensities of the (110) texture were obtained.

3. Reaustenitizing and quenching the textured martensite with the (112) + (111) texture changed the texture of the martensite to a (100) type, but of much weakened intensities. Similarly, reaustenitizing and quenching the textured martensite with the (110) orientation changed the texture of the martensite to a (113) type, but of much weakened intensities. For plates initially rolled to low reductions, reaustenitizing and quenching practically randomized the texture of the martensite.

4. The ballistic limits of the (112) + (111) textured plates increased with increasing texture intensity, or with the amount of rolling reduction, at approximately the same hardness, microstructure, retained austenite, and in-plane mechanical properties. For random-textured plates, the V_{50} protection ballistic limit with 0.50-caliber projectiles was about 2030 to 2100 fps (666 to 689 mps). The ballistic limits of the (112) + (111) textured plates increased from about 2200 fps (722 mps) for the plate rolled 60 percent (texture intensity 3.75) to about 2360 fps (774 mps) for the plates rolled 80 to 90 percent (texture intensity

5.10 to 6.50). The ballistic properties of the (110) textured plates could not be properly evaluated in this study because of the low intensities of texture developed in full-size ballistic plates. Possible variations in the procedure used to produce large-size plates are suggested by this study, and these variations could markedly increase the (110) texture.

5. The ballistic limits of random-textured plates tempered at high temperatures to various retained-austenite contents were all very low, as were the hardnesses. For this range of low hardness and low ballistic limits, the ballistic limit increased with increasing retained-austenite contents, but with decreasing hardness. This unusual ballistic limit—hardness correlation is interesting, because it is opposite to the relation commonly known for high-hardness armor (the ballistic limit generally increases with hardness). This observation may be related to the increased work-hardening capacities with increasing retained austenite, which, on the other hand, decreases the hardness.

6. The ballistic limits of random-textured plates processed to various austenite grain sizes, then quenched, appeared to be little affected by the size of the austenite grains. The similarity in hardness, retained-austenite content, and mechanical and ballistic properties of most of the random-textured plates studied in the present investigation seems to indicate that the properties of random-textured plates were little affected by the thermomechanical history by which the random texture was produced.

7. Although the ballistic limit was substantially increased by increasing the intensity of the (112) + (111) texture, the spalling tendency of the plate upon ballistic impact seemed to have increased also with increasing degrees of texture. The increased resistance to ballistic penetration is believed to be due to the high Young's modulus in the [111] direction and less favorable (lower) resolved stresses on the cleavage plane, and the decreased resistance to spalling is likely a consequence of the microstructural features associated with the textured specimen rather than the degree of texture intensity itself.

8. The spalling resistance of the plate at a constant strain rate might be conveniently determined by a through-thickness, notched tensile test, which approximates the strain conditions of spalling. Results of such tests on the (112) + (111) textured plates with various degrees of texture intensity appeared to be in qualitative agreement with the observed spalling tendencies although at variable ballistic velocities.

Future Work

To provide additional information on the anisotropic properties of textured armor plates, further studies of the effect of improved (111) and (110) textures on the mechanical properties and ballistic performance of the plates are recommended. Ballistic testing at various degrees of obliquity should probably be included in the investigation so that the nature of the anisotropic ballistic properties of textured armor plates can be further explored.

Acknowledgments

The authors wish to express their sincere appreciation to J. G. Bassett, Jr. for making the melts, G. E. Kennedy and C. J. Jennings for their help and advice in hot rolling, to H. E. Knechtel for his assistance in the design of the grips for the through-thickness tension tests, and to K. R. Phillips for conducting the various mechanical tests. A particular note of appreciation is extended to S. Bredja who conducted the ballistic testing. Competent assistance of R. E. Stecik, P. E. Toohill, C. R. Hribal, and C. E. Groff in heat treating, and in making X-ray and metallographic measurements, is sincerely acknowledged. Helpful discussions with L. F. Porter and O. Richmond during the course of this work were most appreciated.

References

1. G. E. Speich, H. Hu, and R. L. Miller: "Effect of Preferred Orientation and Related Metallurgical Parameters in Mechanical Properties and Ballistic Performance of High-Hardness Steel Armor," AMMRC CTR 74-39, June 1974. Contract No. DAAG 46-73-C-0244 AMCMS Code 611102.11.855.

2. H. Hu: "Texture of Metals," Texture, 1974, Vol. 1, No. 4, pp. 233-58.

3. H. Hu and S. R. Goodman: "Texture Transition in Copper," Trans. TMS-AIME, 1963, Vol. 227, pp. 627-39.

4. S. R. Goodman and H. Hu: "Texture Transition in Austenitic Stainless Steels," Trans. TMS-AIME, 1964, Vol. 230, pp. 1413-19.

5. E. B. Kula and S. L. Lopata: "Preferred Orientation in Warm-Worked and Heat-Treated 4340 Steel," Trans. TMS-AIME, 1959, Vol. 215, pp. 980-85.

6. A. Jones and B. Walker: "The Structural State of Austenite During Continuous Hot Strip Mill Rolling," Metal Science, 1974, Vol. 8, pp. 397-406.

7. S. J. Manganello and K. H. Abbott: "Metallurgical Factors Affecting the Ballistic Behavior of Steel Targets," Journal of Materials, 1972, Vol. 7, pp. 231-39.

8. E. Schmid and W. Boas: Plasticity of Crystals, Hughes & Co., Ltd., London, 1950.

9. F. R. Larson: AMMRC, private communication.

10. O. Richmond: "Some Suggestions for Tensile Specimens to Measure Splitting and Spalling Resistance," USS Research Memorandum, October 22, 1975.

11. H. L. Morrison and O. Richmond: "Large Deformation of Notched Perfectly Plastic Tensile Bars," Trans. ASME, Journal of Applied Mechanics, 1972, Vol. 39, Series E, pp. 971-77.

Table I

Chemical Composition of Armor Steel in Weight Percent

Ingot	C	Mn	P	S	Si	Cu	Ni	Mo	V	Al	N	O ppm
A	0.40	0.58	0.003	0.001	1.26	1.00	5.15	0.45	0.090	0.068	0.006	51
B-1	0.36	0.63	0.003	0.003	1.13	1.04	5.14	0.43	0.096	0.071	0.005	38
B-4	0.38	0.63	0.003	0.003	1.14	1.00	5.30	0.43	0.094	0.071	0.005	35

Ingot A - for retained-austenite and austenite-grain-size studies.

Ingot B - for texture studies.

1) From plate rolled 60% to 0.55-in. thick.

4) From plate rolled 90% to 0.55-in thick.

(See procedures for details.)

Table II

Texture of Armor-Steel Plate for Retained-Austenite and Austenite-Grain-Size Studies

Austenitizing Treatment	Specimen Section*	X-Ray Intensity, Random Units (110)	(200)	(211)	(310)	(222)
1500°F-1 hr/WQ	S	1.01	1.26	1.09	0.95	1.28
	1/4 t	0.95	0.98	0.86	0.76	1.21
	1/2 t	0.92	1.00	0.88	0.83	1.23
	Avg	0.92	1.03	0.88	0.83	1.24
1900°F-1 hr/WQ	S	1.10	1.06	0.92	0.81	0.88
	1/4 t	0.98	0.93	0.91	0.78	1.21
	1/2 t	0.98	0.87	0.97	0.91	1.09
	Avg	1.02	0.95	0.93	0.83	1.06
2300°F-1 hr/WQ	S	0.90	1.47	0.60	0.69	1.70
	1/4 t	0.88	0.73	1.23	0.67	0.85
	1/2 t	0.78	0.80	1.00	0.56	1.05
	Avg	0.85	1.00	0.94	0.64	1.20

* S = Surface; 1/4 t = Quarterthickness below surface; 1/2 t = Mid-thickness.

Table III

Mechanical Properties of Armor-Steel Plates Processed by Quenching Deformed Austenite (Texture Studies)

Hot-Rolling Reduction, %	Yield Strength (0.2% Offset), ksi (MPa)		Tensile Strength, ksi (MPa)		Reduction in Area, %		Total Elongation in 1 inch, %	
	L	T	L	T	L	T	L	T
90	225.5 (1555)	245.9 (1695)	298.6 (2059)	318.1 (2193)	51.3	31.3	15.0	10.0
80	230.3 (1588)	250.0 (1724)	303.2 (2091)	315.9 (2178)	50.0	34.0	16.0	11.5
70	219.1 (1511)	231.8 (1598)	303.2 (2091)	313.0 (2158)	51.3	35.0	15.0	12.3
60	229.5 (1582)	238.0 (1641)	293.8 (2026)	308.1 (2124)	51.3	36.1	14.0	11.8

Table IV

Mechanical Properties of Armor-Steel Plates
Processed by Quenching Recrystallized Austenite
(Texture Studies)

Hot-Rolling Reduction, %	Yield Strength (0.2% Offset), ksi (MPa)		Tensile Strength, ksi (MPa)		Reduction in Area, %		Total Elongation in 1 inch, %	
	L	T	L	T	L	T	L	T
90	225.8 (1557)	225.4 (1554)	295.8 (2040)	292.9 (2020)	52.2	42.9	15.5	13.0
80	219.8 (1516)	220.8 (1522)	299.3 (2064)	301.4 (2078)	52.2	39.0	15.5	12.8
70	217.5 (1500)	220.9 (1523)	295.7 (2039)	294.0 (2027)	49.6	39.9	14.0	11.5
60	212.0 (1462)	214.1 (1476)	299.6 (2066)	292.5 (2017)	43.7	40.0	14.0	12.3

Table V

Mechanical Properties of Armor-Steel Plates Processed by Reaustenitizing and Quenching (Texture Studies)

Hot-Rolling Reduction, %	Yield Strength (0.2% Offset), ksi (MPa) L	Yield Strength (0.2% Offset), ksi (MPa) T	Tensile Strength, ksi (MPa) L	Tensile Strength, ksi (MPa) T	Reduction in Area, % L	Reduction in Area, % T	Total Elongation in 1 inch, % L	Total Elongation in 1 inch, % T
Martensite Transformed from Deformed Austenite								
90	195.5 (1348)	204.4 (1409)	298.7 (2060)	299.8 (2067)	50.4	38.2	15.8	13.0
80	204.8 (1412)	211.4 (1458)	303.9 (2095)	300.4 (2071)	48.4	40.3	15.8	13.0
70	203.4 (1402)	204.2 (1408)	302.9 (2088)	301.3 (2077)	45.6	37.4	14.5	12.3
Martensite Transformed from Recrystallized Austenite								
90	192.5 (1327)	191.8 (1322)	305.4 (2106)	300.2 (2070)	50.9	38.2	15.8	13.0
80	207.4 (1430)	202.0 (1393)	299.1 (2062)	302.0 (2082)	51.3	39.4	15.0	13.5
70	203.1 (1400)	205.2 (1415)	303.6 (2093)	304.0 (2096)	44.8	37.8	15.0	12.8

Note: For plates initially rolled 60 percent, insufficient material was available to conduct these tests.

Table VI

Mechanical Properties of Armor-Steel Plates Heat-Treated to Various Amounts of Retained Austenite
(Retained-Austenite Studies)

Austenitizing Treatment	Tempering Treatment	Yield Strength,* ksi (MPa)	Tensile Strength, ksi (MPa)	Reduction in Area, %	Total Elong in 1 inch, %	Retained Austenite, %
1650°F-1 hr and WQ	1100°F-1 hr/WQ	174.4 (1202)	211.5 (1458)	41.3	14.5	4.4
	1150°F-1 hr/WQ	163.6 (1128)	197.2 (1360)	42.0	17.0	7.1
	1200°F-1 hr/WQ	133.4 (920)	200.4 (1382)	38.5	19.3	15.6
	1250°F-1 hr/WQ	151.6 (1045)	233.0 (1607)	26.8	15.0	12.9
	1250°F-1 hr/Liq. N_2 - 30 min	169.0 (1165)	238.2 (1642)	28.0	10.0	3.7
	1300°F-1 hr/WQ	182.6 (1259)	287.8 (1984)	19.4	12.8	10.2

* 0.2% offset

Table VII

Mechanical Properties of Armor-Steel Plates
Heat-Treated to Various Austenite Grain Sizes
(Austenite-Grain-Size Studies)

Austenitizing Treatment	Austenite Grain Size, ASTM No.	Yield Strength,* ksi (MPa)	Tensile Strength, ksi (MPa)	Reduction in Area, %	Total Elong in 1 inch, %
1500°F-1 hr/WQ	8	224.2 (1546)	311.9 (2151)	35.6	11.3
1700°F-1 hr/WQ	7	223.6 (1542)	305.4 (2106)	43.2	12.8
1900°F-1 hr/WQ	7	214.5 (1479)	312.2 (2153)	38.9	12.3
2100°F-1 hr/WQ	3	213.6 (1473)	305.7 (2108)	24.6	11.0
2300°F-1 hr/WQ	0	199.1 (1373)	253.6 (1749)	5.0	3.8**

* 0.2% offset
** Quench crack in specimen

Table VIII

Ballistic Performance of Armor-Steel Plates
Processed by Quenching the Deformed Austenite (Texture Studies)

Hot-Rolling Reduction, %	Texture Type	Texture Intensity	Test Plate Thickness, in.	Test Plate Hardness, RC	Retained Austenite, %	Ballistic Limit, V50, fps
90	Strong (112) + (111)	6.50	0.467	54.5	3.3	2354
80		5.10	0.467	54.5	2.7	2364
70		3.95	0.467	54.0	3.2	2305
60		3.75	0.465	54.0	3.7	2204

Table IX

Ballistic Performance of Armor-Steel Plates Processed by Quenching the Recrystallized Austenite (Texture Studies)

Hot-Rolling Reduction, %	Temperature Recrystal. Anneal, °F	Texture Type	Texture Intensity	Test Plate Thickness, in.	Test Plate Hardness, R_C	Retained Austenite, %	Ballistic Limit, V_{50}, fps
90	1800	Weak (110) to Nearly Random	1.40	0.462	54.0	5.1	2027
80	1800		1.30	0.465	53.0	6.0	2029
70	1800		1.20	0.466	54.0	5.2	1959
60	1800		1.20	0.466	54.0	6.8	2032

Table X

Ballistic Performance of Armor-Steel Plates Processed by Reaustenitizing and Quenching Plates Originally Quenched to Martensite from Deformed or from Recrystallized Austenite (Texture Studies)

Hot-Rolling Reduction, %	Reausten-itizing Temp, °F	Texture Type	Texture Intensity	Test Plate Thickness, in.	Test Plate Hardness, RC	Retained Austenite, %	Ballistic Limit, V_{50}, fps
Reheat Treatment of Plates Produced by Quenching Deformed Austenite							
90	1800	Weak (100) to Nearly Random	1.70	0.471	53.0	6.0	2002
80	1800		1.30	0.471	54.0	6.4	2105
70	1800		1.20	0.453	54.0	6.8	1950
60	1800		1.20	-	-	-	- *
Reheat Treatment of Plates Produced by Quenching Recrystallized Austenite							
90	1800	Weak (113) to Nearly Random	1.40	0.467	52.0	6.9	2092
80	1800		1.35	0.469	54.5	6.0	2029
70	1800		1.30	0.463	53.5	6.5	2031
60	1800		1.30	-	-	-	- *

*Insufficient material for ballistic testing.

Table XI

Ballistic Performance of Armor-Steel Plates as Influenced by the Amount of Retained Austenite (Retained-Austenite Studies)

Austenitizing Treatment	Tempering Treatment	Texture Type	Test Plate Thickness, in.	Test Plate Hardness, R_C	Retained Austenite, %	Ballistic Limit, V_{50}, fps
1650°F-1hr/WQ	1100°F-1 hr/WQ	Practically Random	0.502	46.0	4.4	1472
	1150°F-1 hr/WQ		0.501	44.0	7.1	1548
	1200°F-1 hr/WQ		0.501	41.0	15.6	1630
	1250°F-1 hr/WQ		0.501	44.0	12.9	1534
	1300°F-1 hr/WQ		0.501	51.0	10.2	1462
	1250°F-1 hr/Liq N_2 - 30 min		0.502	46.5	3.7	1367

Quenched plates were all tempered 1 hr at 350°F, surface-ground to remove scale and decarburized layer, and then tested.

Table XII

Ballistic Performance of Armor-Steel Plates Austenitized at Various Temperatures (Austenite-Grain-Size Studies)

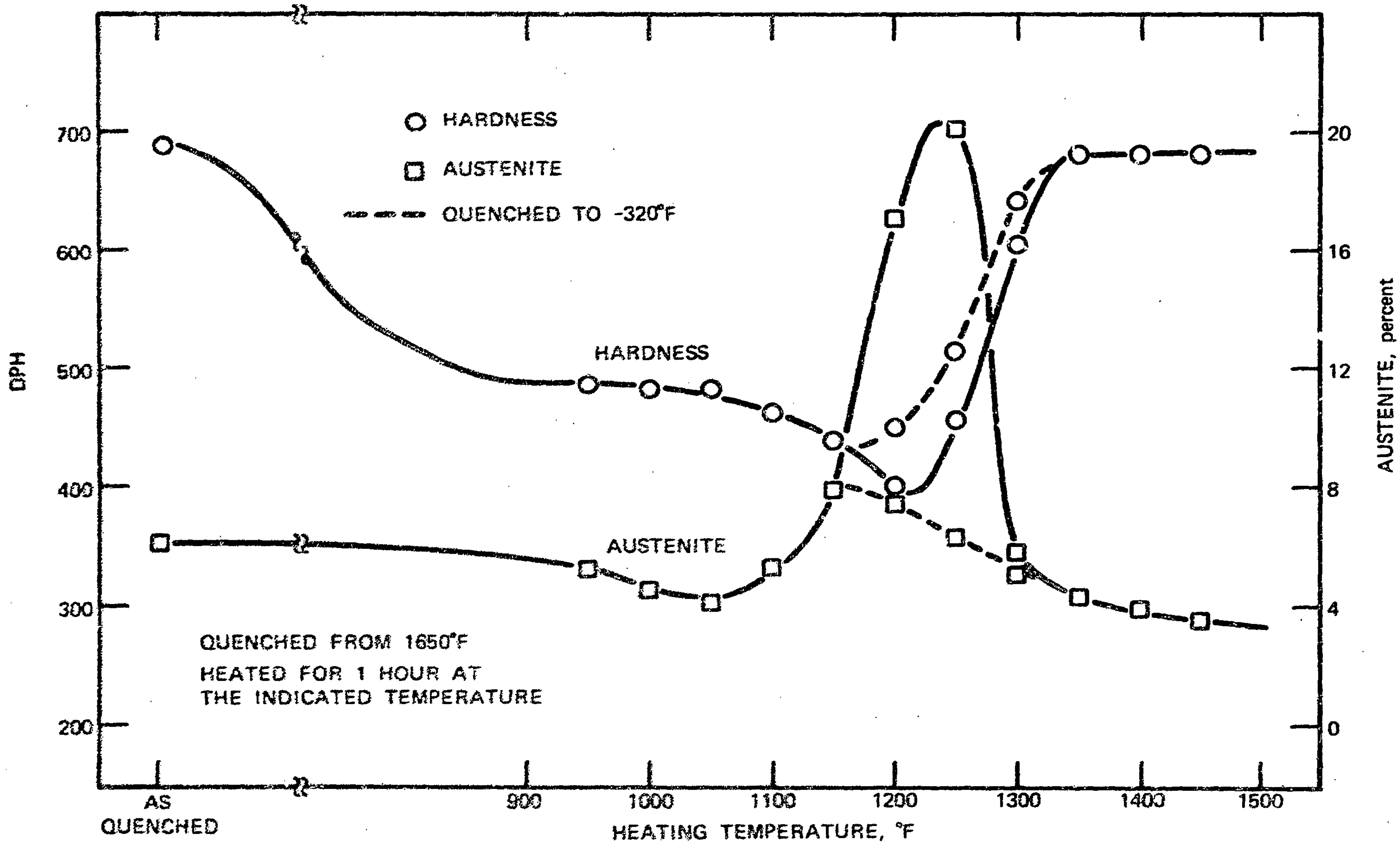
Austenitizing Treatment	Austenite G.S., ASTM No.	Texture Type	Test Plate Thickness, in.	Test Plate Hardness, R_C	Retained Austenite %	Ballistic Limit, V50, fps
1500°F-1 hr/WQ	8		0.501	55.0	7.5	2066
1700°F-1 hr/WQ	7	Practically	0.501	54.0	7.4	2068
1900°F-1 hr/WQ	7	Random	0.501	54.5	6.2	2085
2100°F-1 hr/WQ	3		0.501	54.0	6.3	2115
2300°F-1 hr/WQ	0		0.501	52.5	7.2	2025

Quenched plates were all tempered 1 hr at 350°F, surface-ground to remove scale and decarburized layer, and then tested.

Table XIII

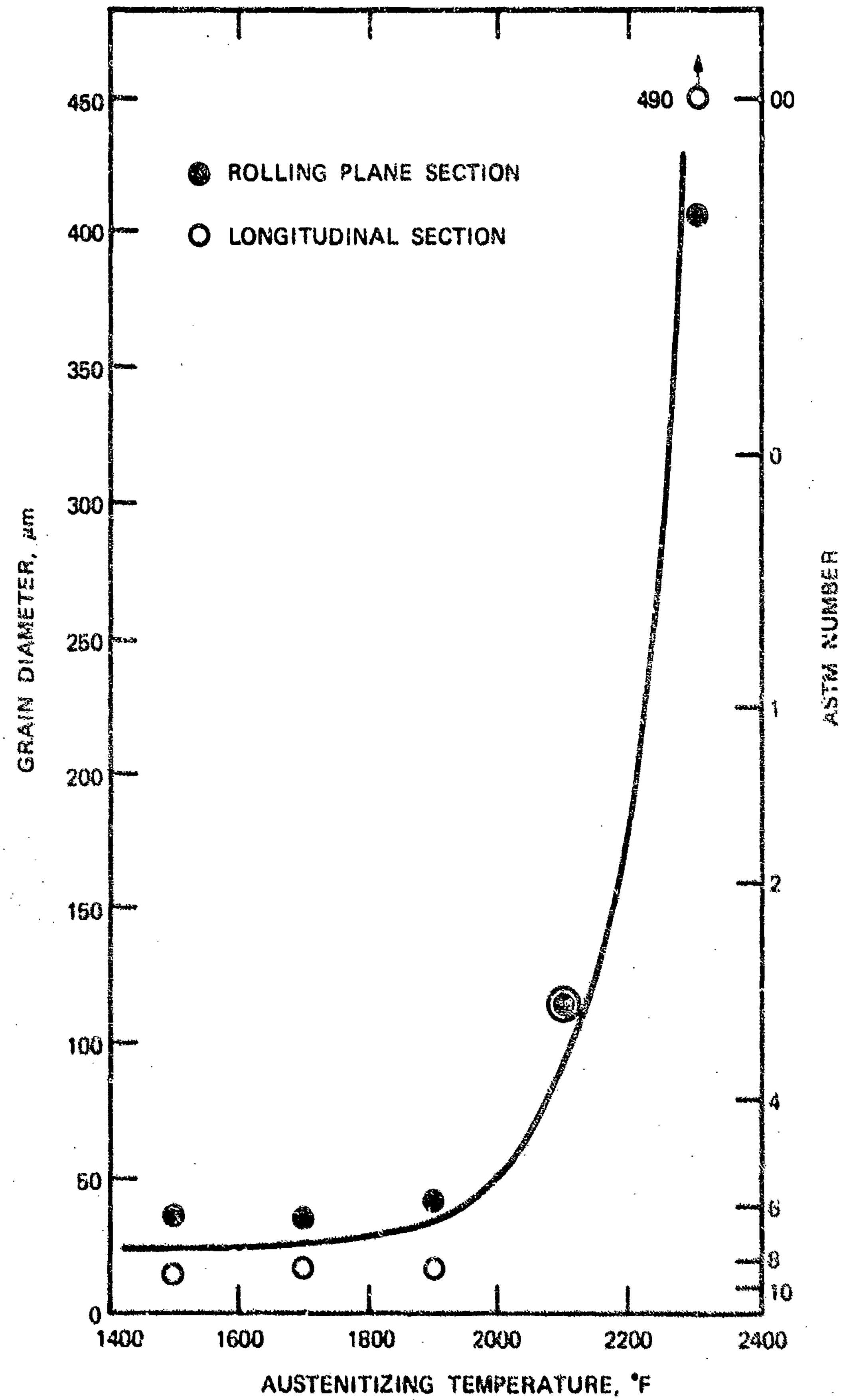
Through-Thickness Notched Tensile Strength
of Armor Steel Plates Processed to Various Textures
(Texture Studies)

Hot-Rolling Reduction, %	(1) Martensite by Quenching Deformed Aust		(2) Martensite by Quenching Recryst Aust		(3) Martensite by Reaustenitizing & Quenching (1)		(4) Martensite by Reaustenitizing & Quenching (2)	
	ksi	(MPa)	ksi	(MPa)	ksi	(MPa)	ksi	(MPa)
90	346.6	(2390)	419.8	(2895)	-	-	-	-
80	391.8	(2701)	-	-	-	-	-	-
70	385.7	(2659)	-	-	-	-	-	-
60	415.0	(2861)	424.1	(2924)	434.4	(2995)	435.9	(3006)

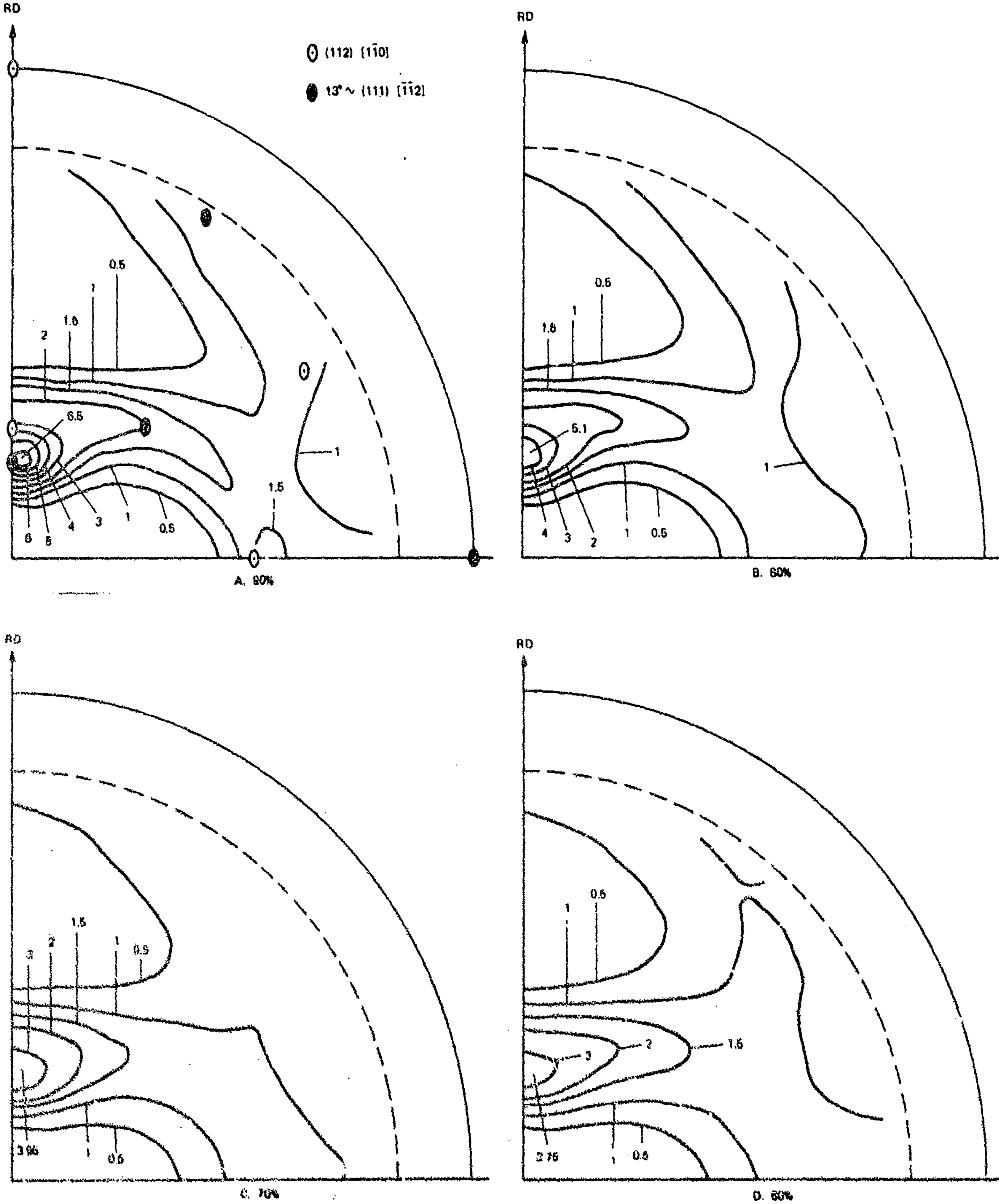


THE CRITICAL RANGE OF TEMPERATURE OF THE ARMOR STEEL

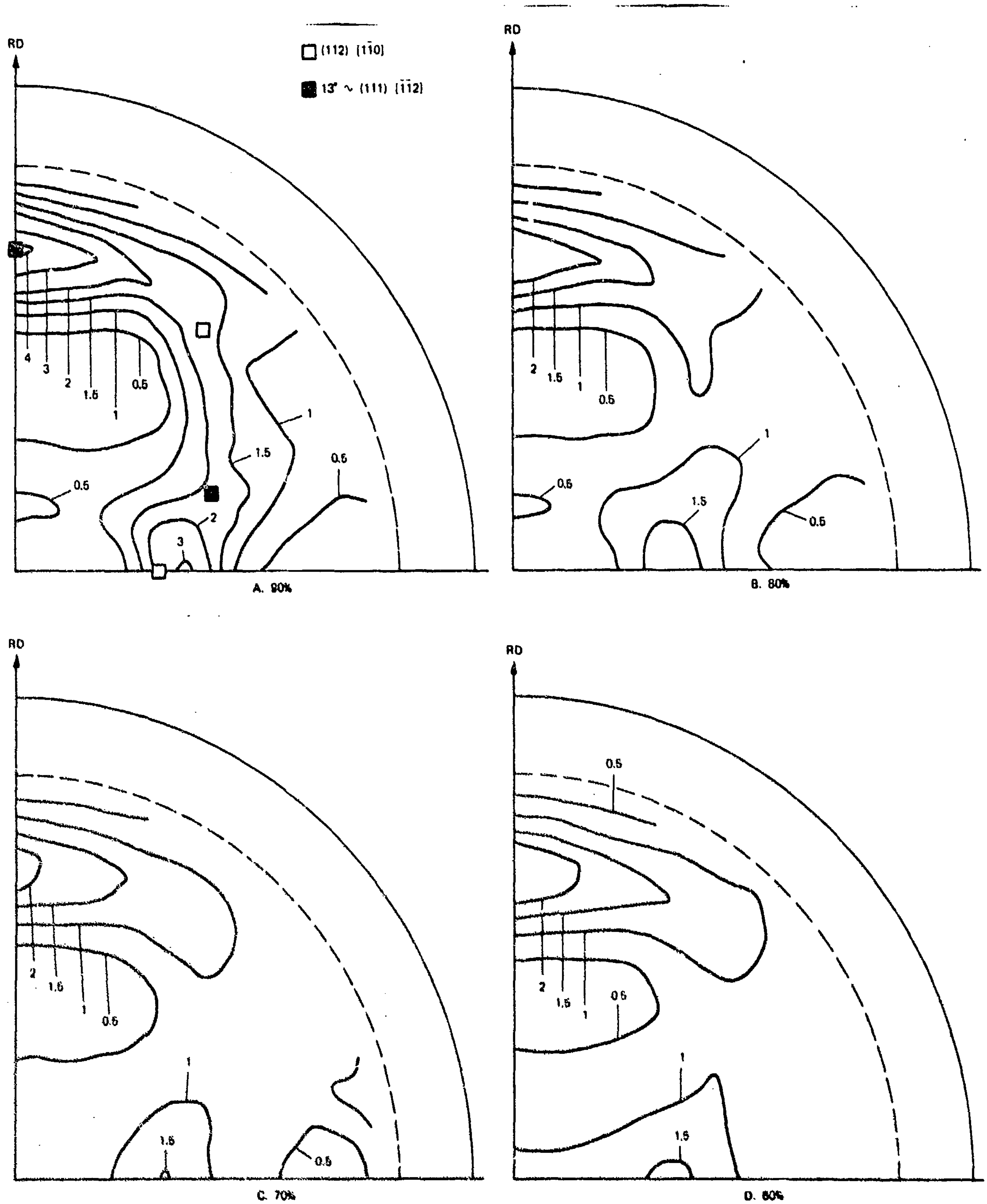
RL-61-36 76-H-018(061) Figure 1



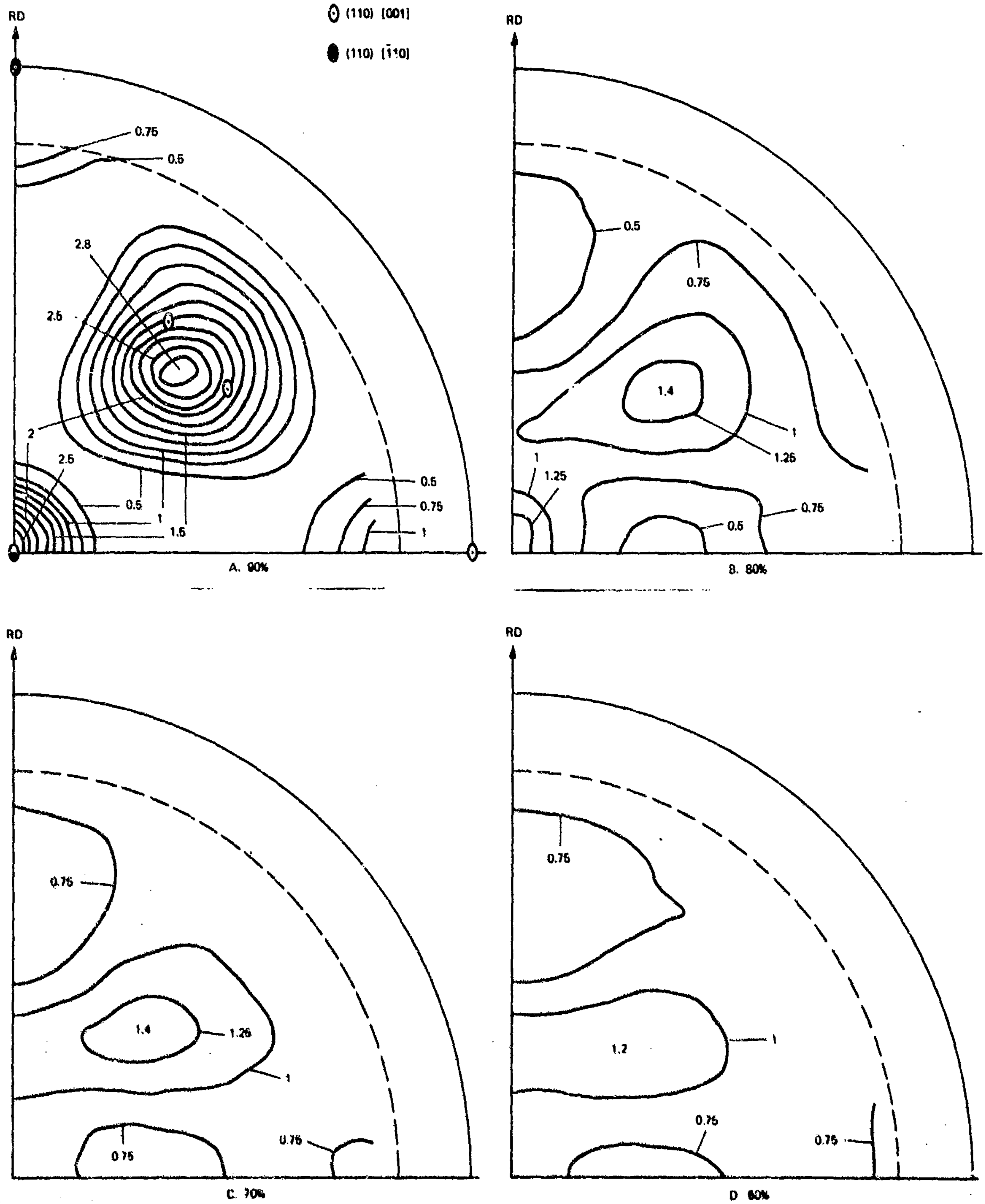
TEMPERATURE DEPENDENCE OF AUSTENITE GRAIN SIZE



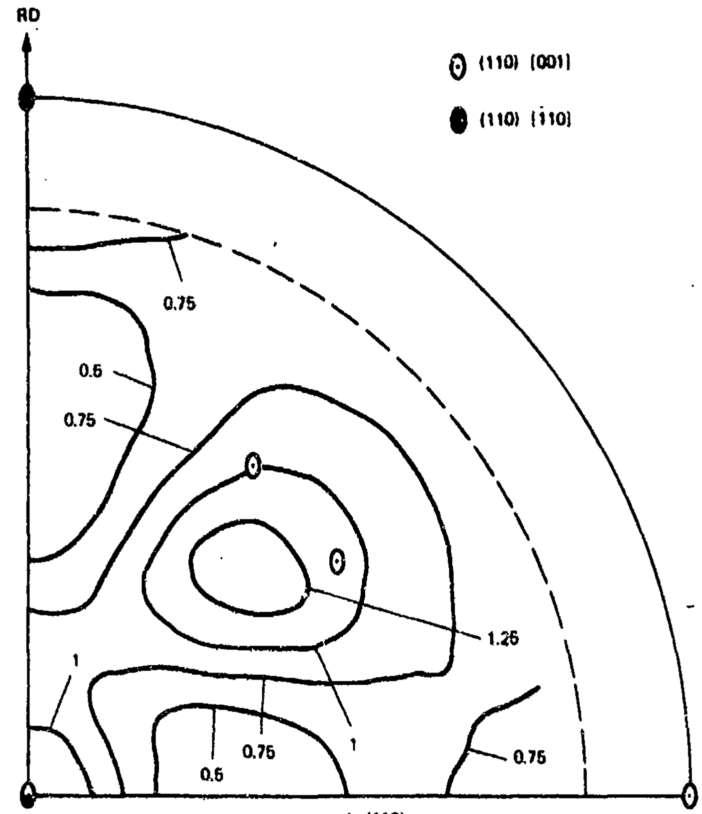
(110) POLE FIGURES SHOWING TEXTURE OF ARMOR-STEEL PLATES ROLLED TO VARIOUS REDUCTIONS AT 1600°F TO 0.55 INCH THICK AND QUENCHED. A. 90%, B. 80%, C. 70%, AND D. 60%.



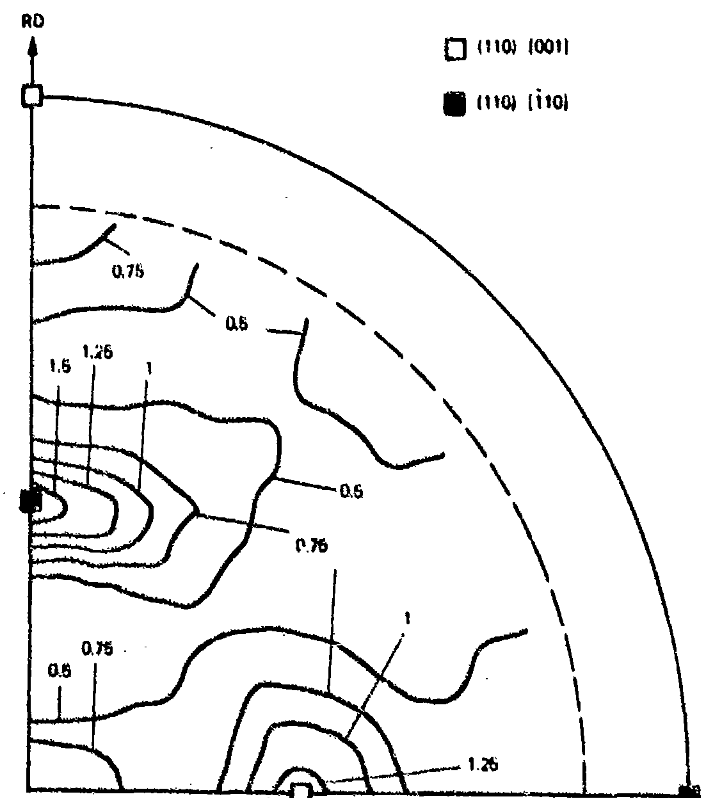
(200) POLE FIGURES SHOWING TEXTURE OF ARMOR-STEEL PLATES ROLLED TO VARIOUS REDUCTIONS AT 1600°F TO 0.55 INCH THICK AND QUENCHED. A. 90%, B. 80%, C. 70%, AND D. 60%.



(110) POLE FIGURES SHOWING TEXTURE OF ARMOR-STEEL SPECIMENS ROLLED TO VARIOUS REDUCTIONS AT 1350°F, RECRYSTALLIZED AT 1800°F, THEN QUENCHED. A. 90% TO 0.10 INCH THICK. B. 80% TO 0.20 INCH THICK. C. 70% TO 0.15 INCH THICK, AND D. 60% TO 0.20 INCH THICK.

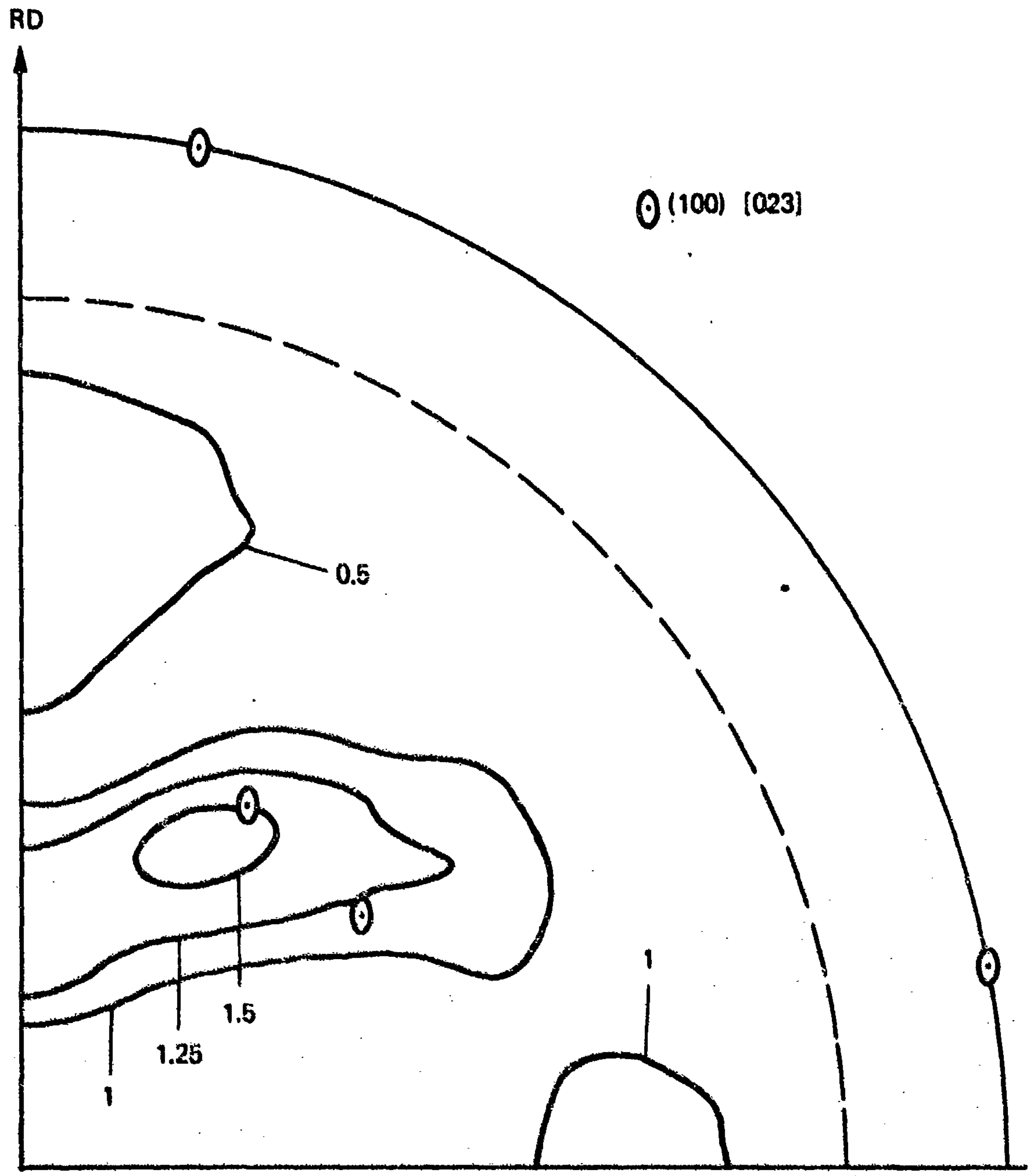


A (110)

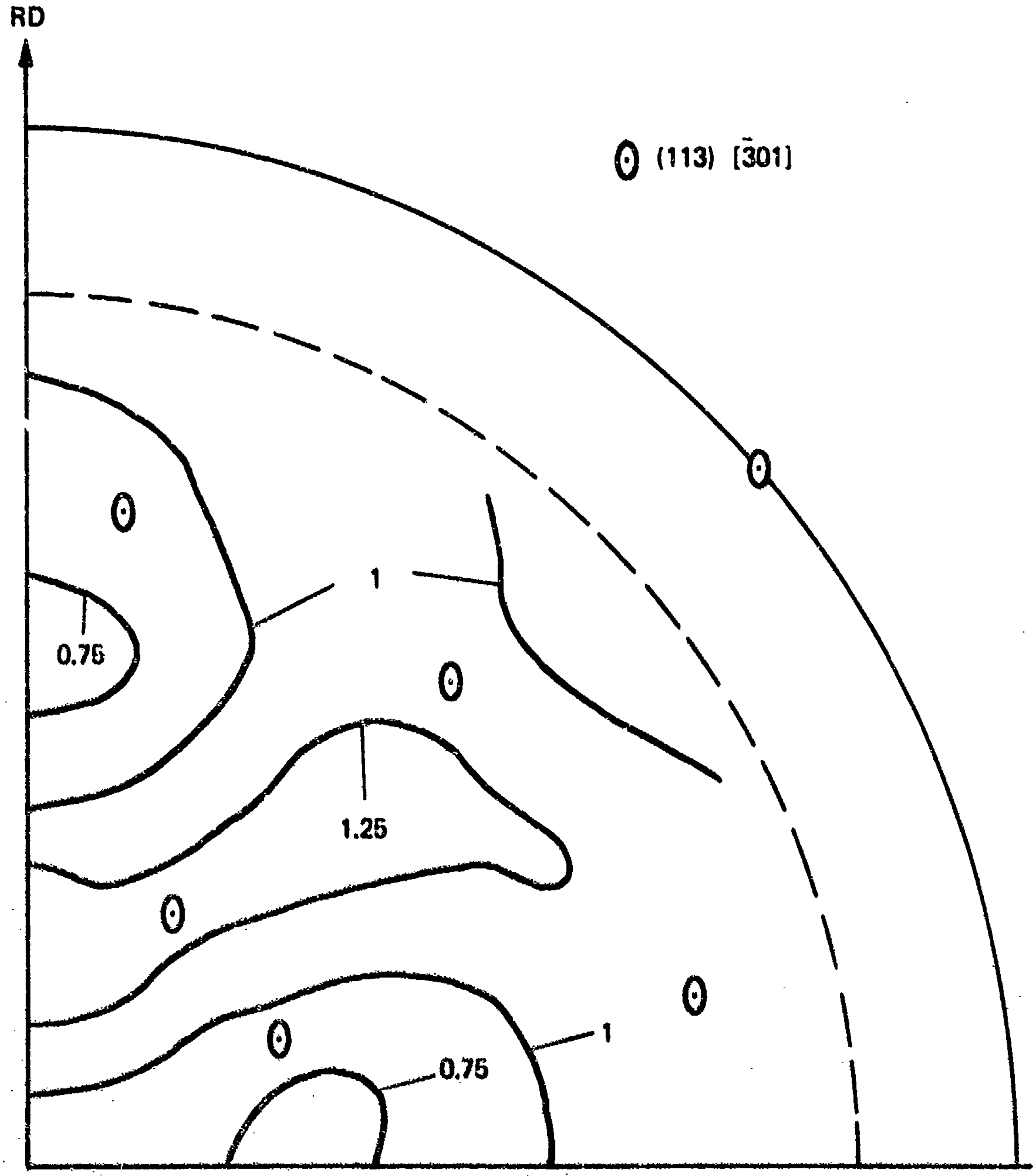


B (200)

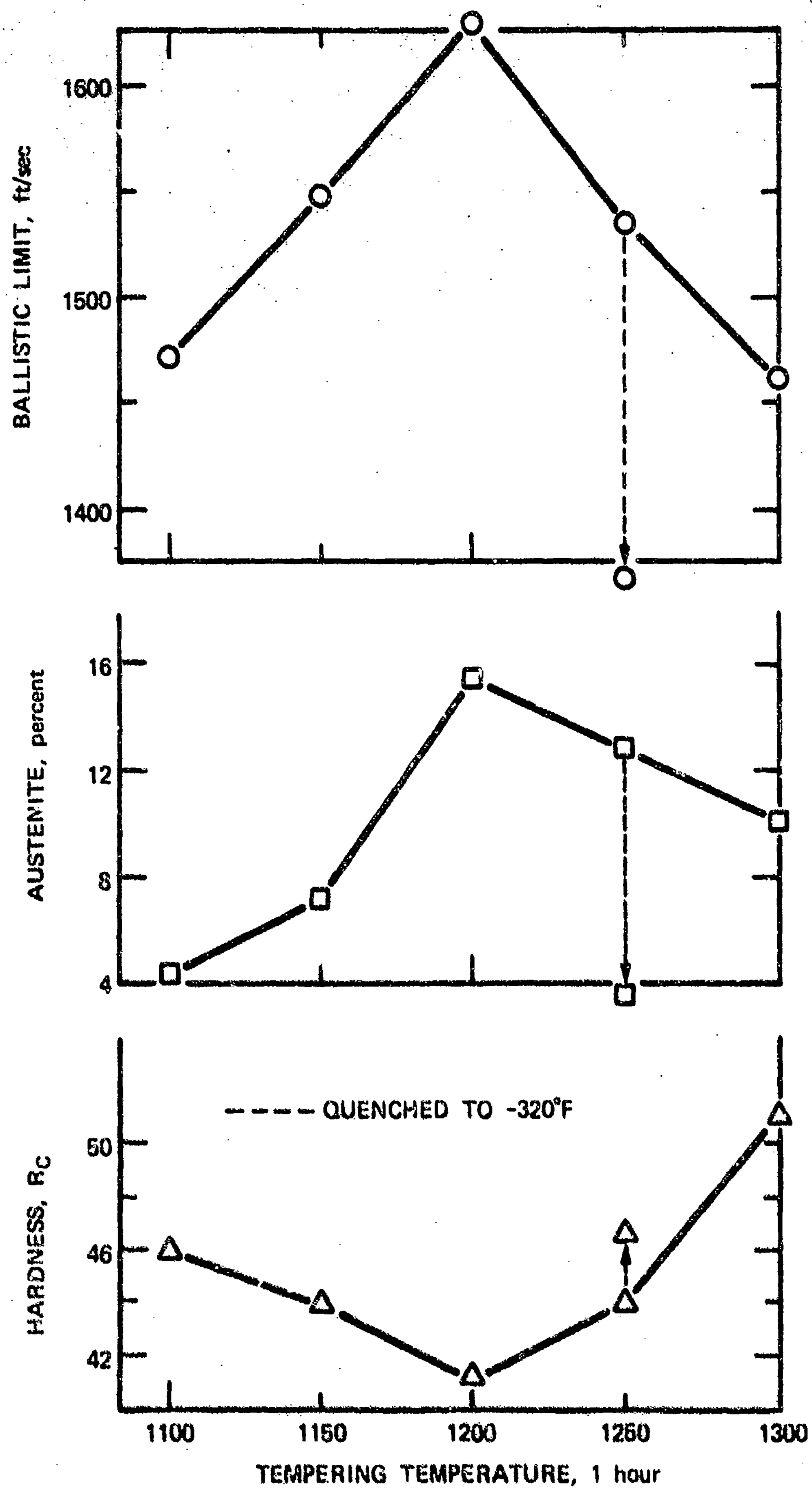
TEXTURE OF ARMOR-STEEL PLATE ROLLED 90% AT 1700 TO 1500°F TO 0.55 INCH THICK, RECRYSTALLIZED AT 1800°F, THEN QUENCHED. A. (110) POLE FIGURE, B. (200) POLE FIGURE.



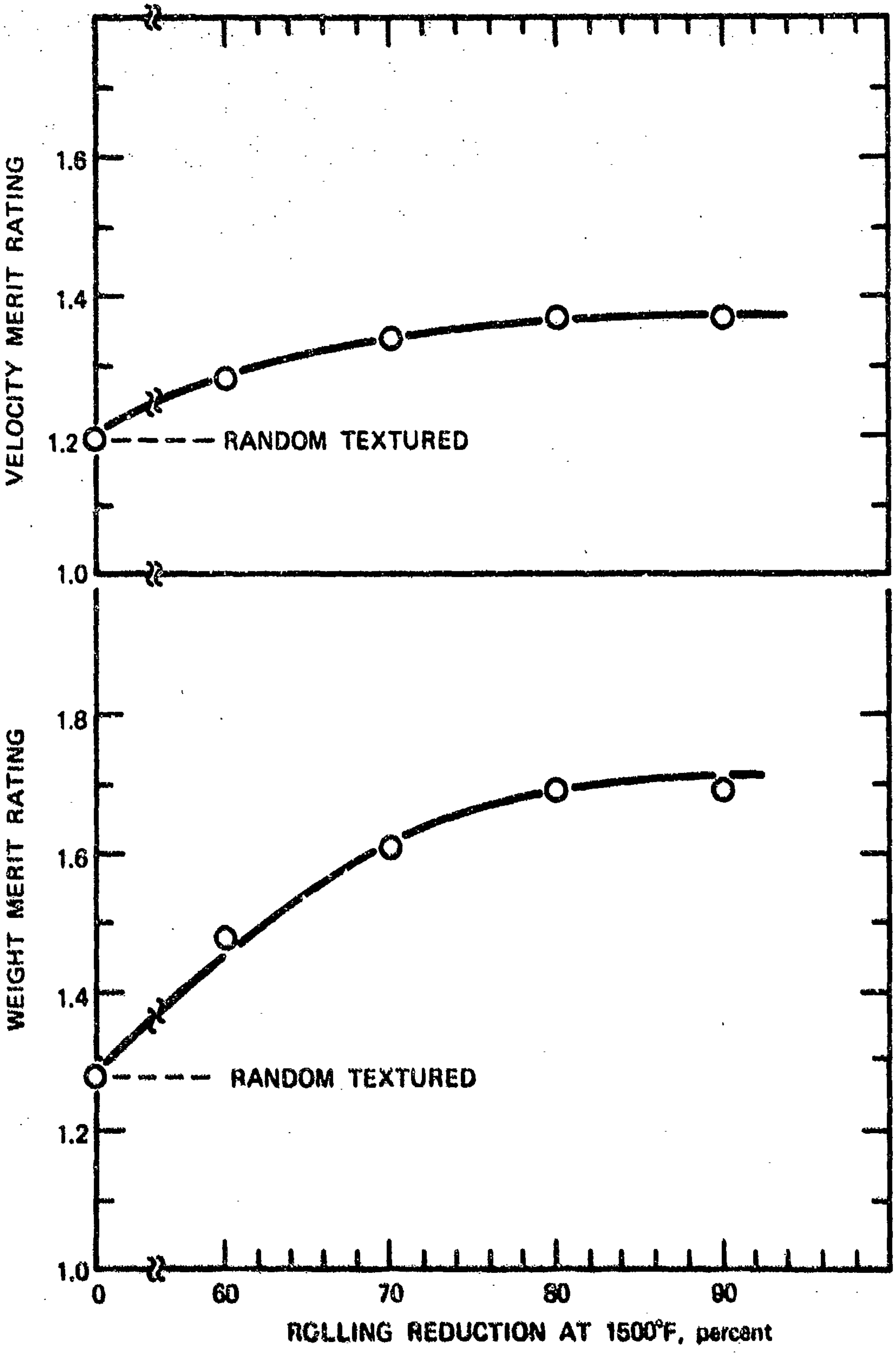
(110) POLE FIGURE SHOWING TEXTURE OF ARMOR-STEEL PLATE AFTER REAUSTENITIZING AT 1800°F AND QUENCHING. INITIAL TEXTURE OF THE PLATE IS SHOWN IN FIGURE 3A.



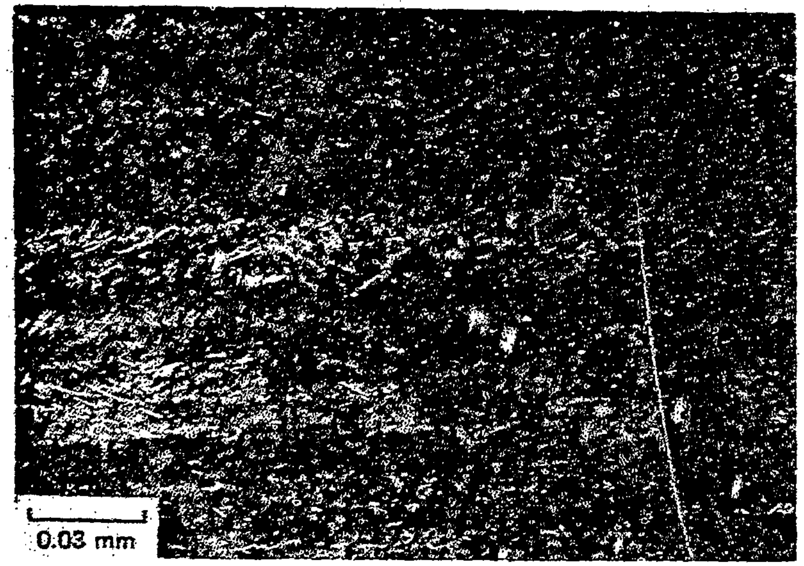
(110) POLE FIGURE SHOWING TEXTURE OF ARMOR-STEEL PLATE AFTER REAUSTENITIZING AT 1800°F AND QUENCHING. INITIAL TEXTURE OF THE PLATE IS SHOWN IN FIGURE 6A.



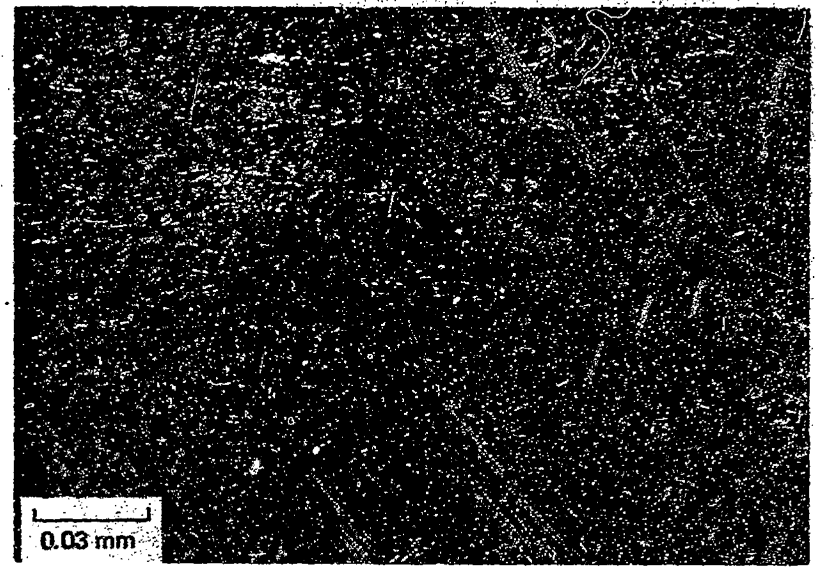
RELATIONSHIP BETWEEN HARDNESS, RETAINED AUSTENITE, AND BALLISTIC LIMIT AFTER TEMPERING AT FIVE INTERMEDIATE TEMPERATURES, AND AFTER QUENCHING IN LIQUID NITROGEN.



WEIGHT AND VELOCITY MERIT RATING AS A FUNCTION OF ROLLING REDUCTION, HENCE TEXTURE INTENSITY.



Longitudinal



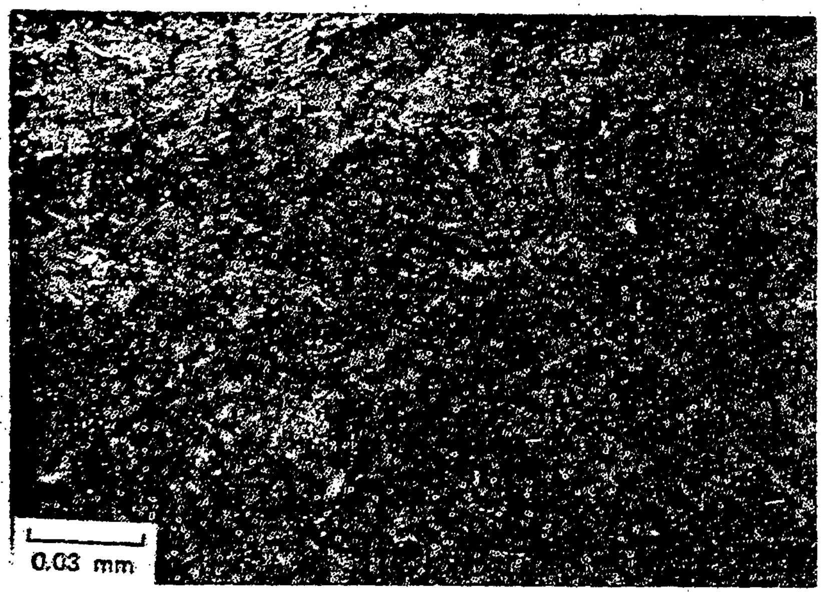
Transverse

Rolling Plane

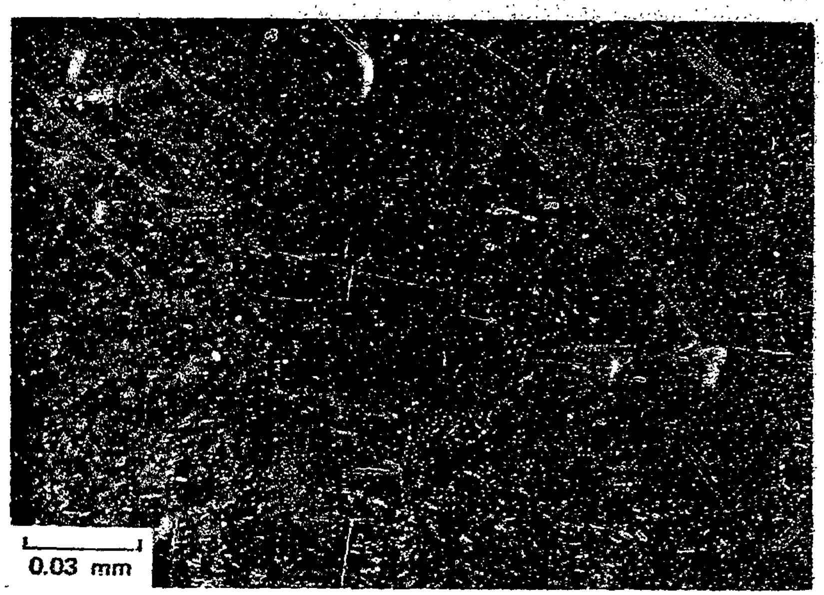
VP 654
VP 659
VP 673

Microstructure of the Plate Rolled 90 Percent Then Quenched. X500.

Figure 11-A



Longitudinal



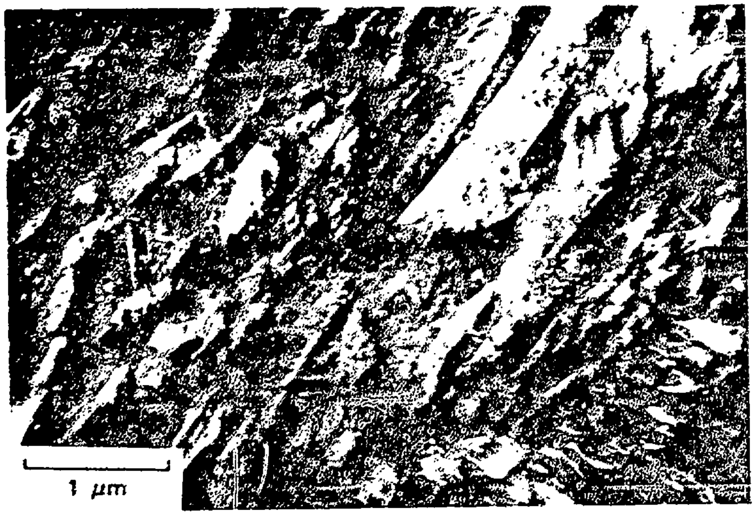
Transverse

Rolling Plane

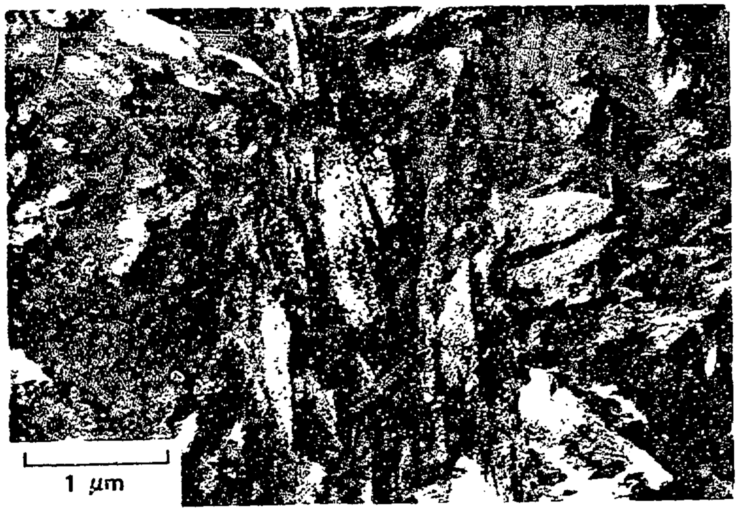
VP 669
VP 670

Microstructure of the Plate Rolled 60 Percent Then Quenched. X500.

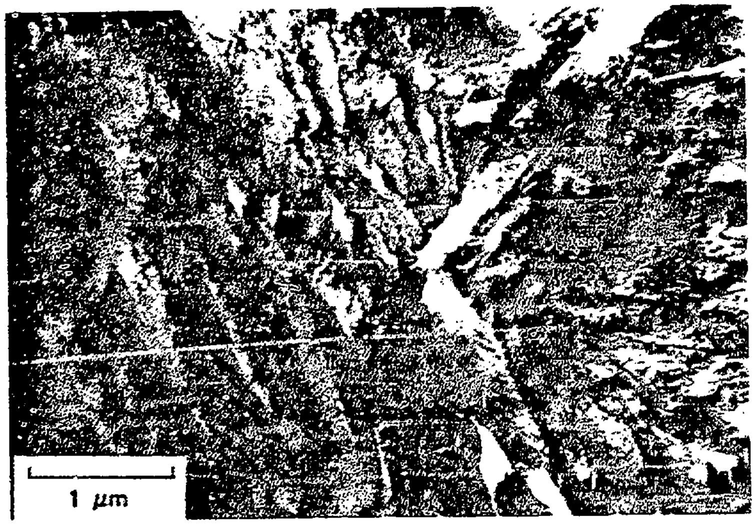
Figure 11-B



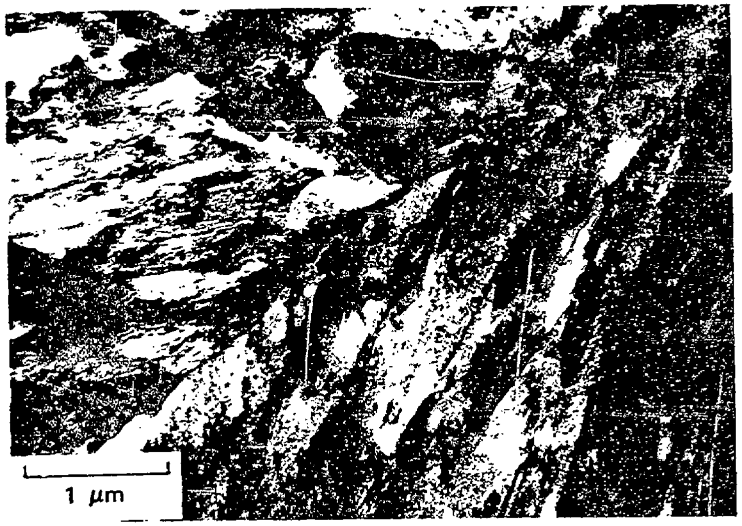
Longitudinal-Section
Rolled 90 Percent at
1500°F



Transverse Section Rolled
90 Percent at 1500°F



Longitudinal Section Rolled
60 Percent at 1500°F

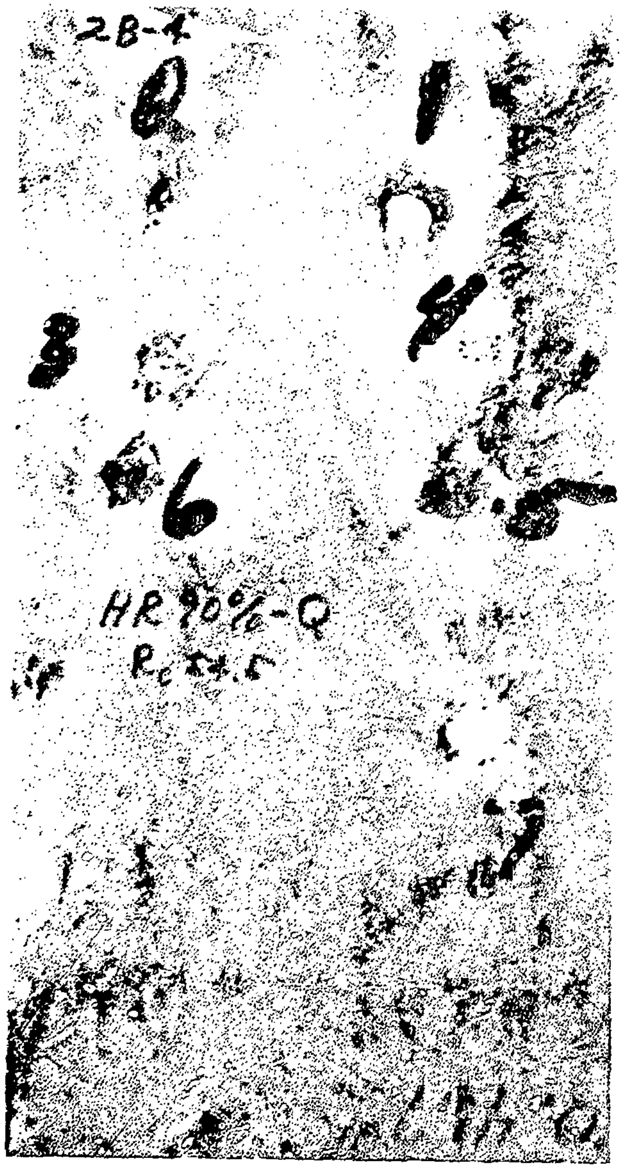


Transverse Section Rolled
60 Percent at 1500°F

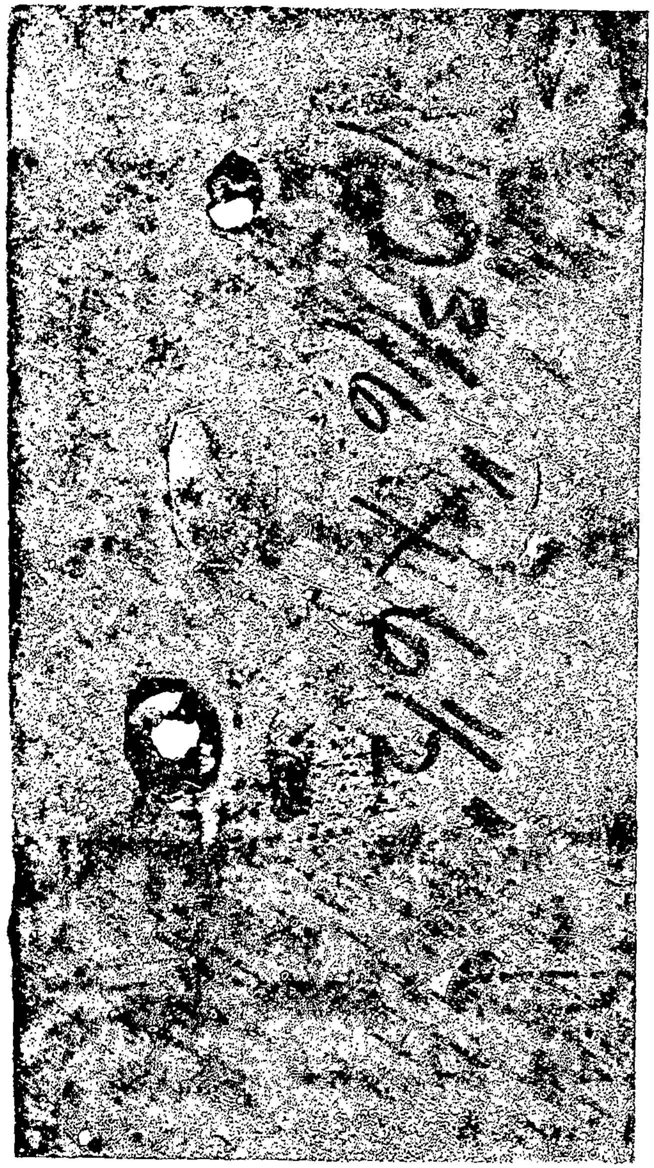
009385
009382
009376
009373

Transmission Electron Micrographs Showing Martensite Structures of Quenched and Tempered Plates. X19,000.

Figure 12



Front

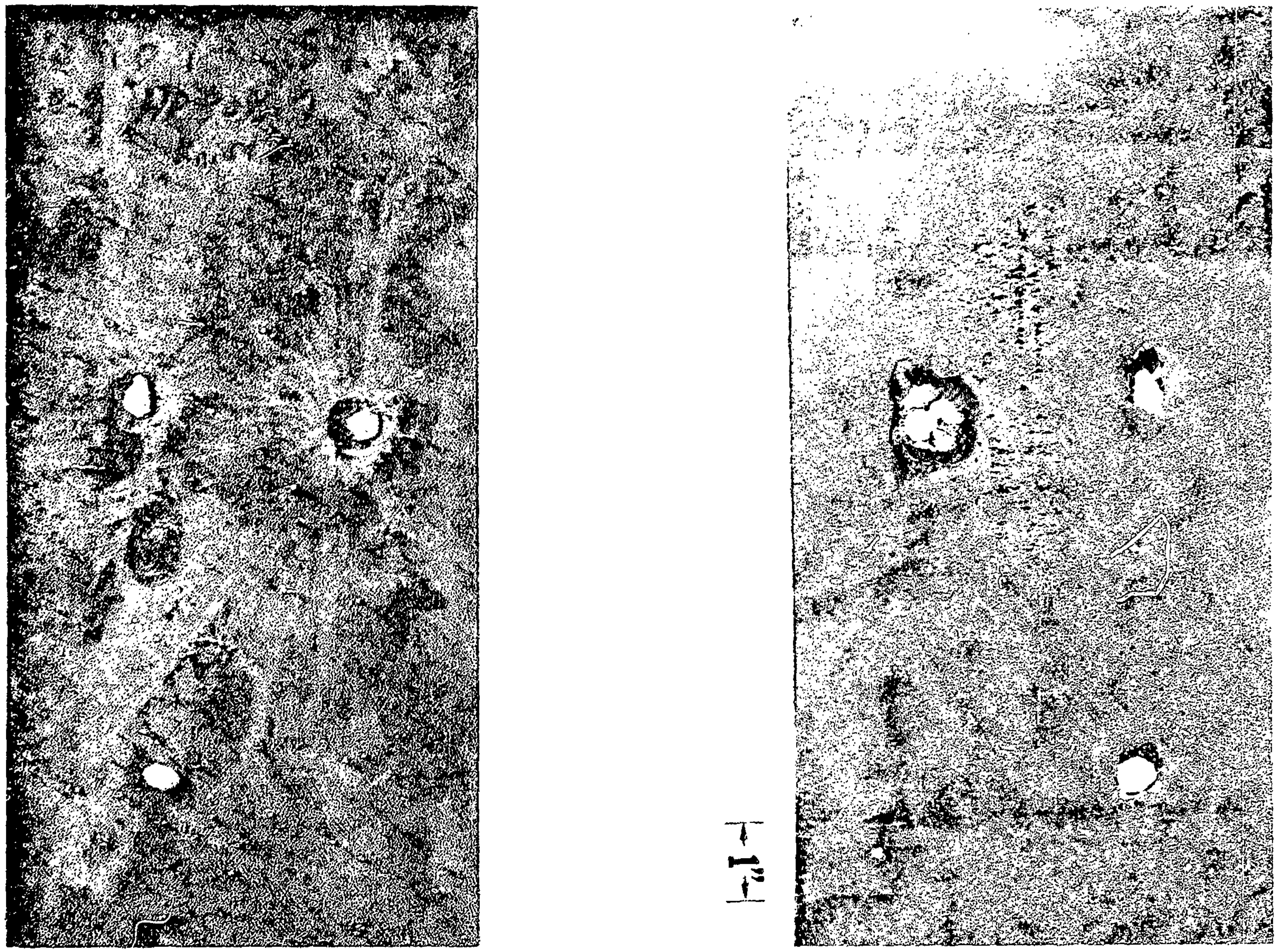


Back

Ballistic-Tested Plate, Rolled 90 Percent at 1500°F Prior to Quenching.

P-5498B-4
P-5498B-7

Figure 13-A



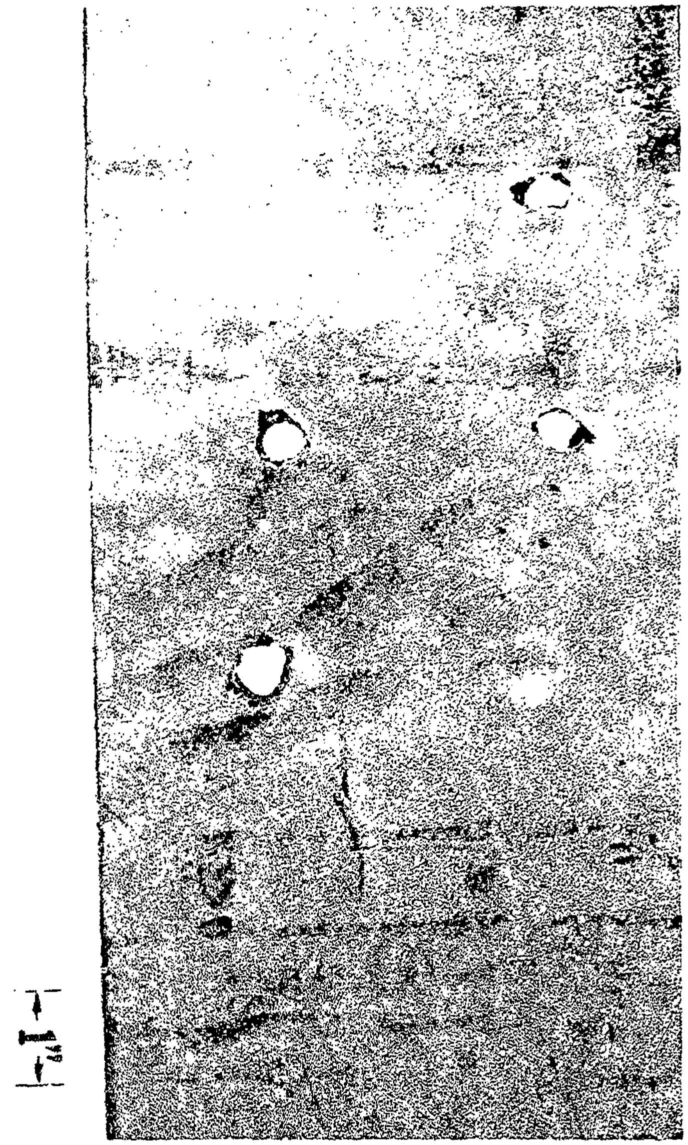
Front Back

Ballistic-Tested Plate, Rolled 80 Percent at 1500°F Prior to Quenching.

P-5498B-2
P-5498B-10

Figure 13-B

Front



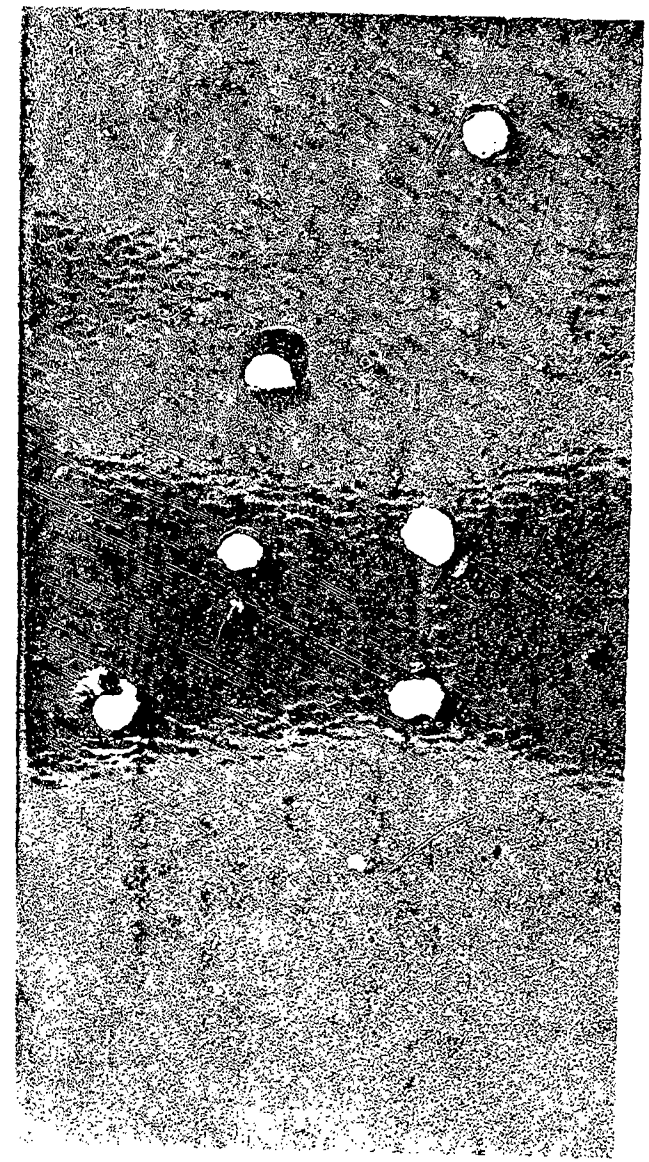
Back

Ballistic-Tested Plate, Rolled 70 Percent at 1500°F Prior to Quenching.

P-5498B-3
P-5498B-9

Figure 13-C

Front



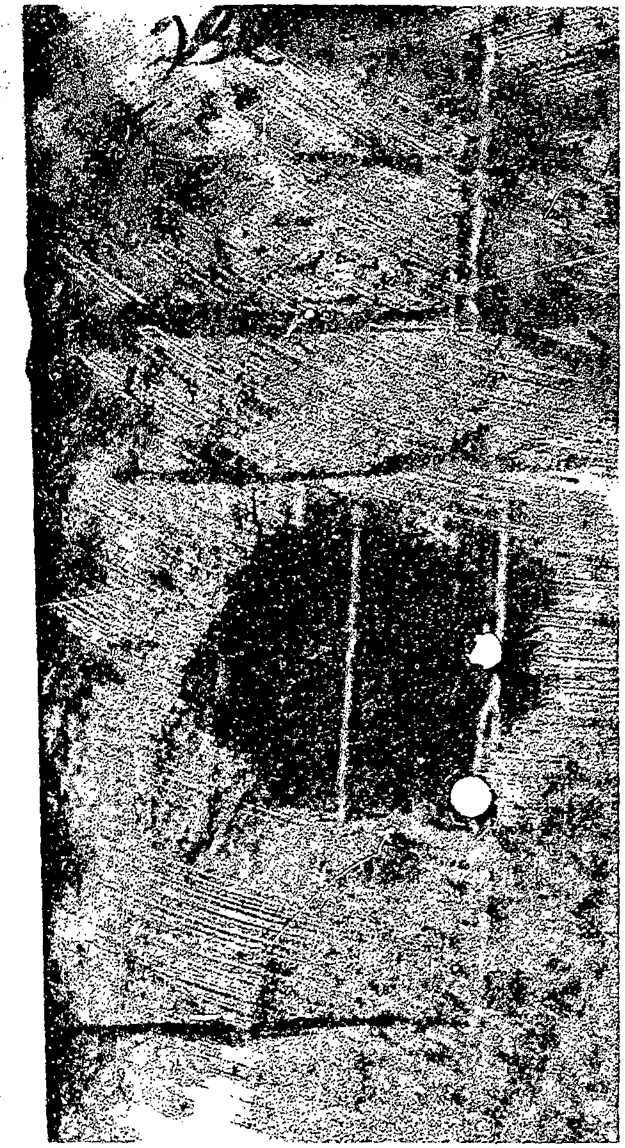
Back

Ballistic-Tested Plate, Rolled 60 Percent at 1500°F Prior to Quenching.

P-5498B-1
P-5498B-8

Figure 13-D

Front



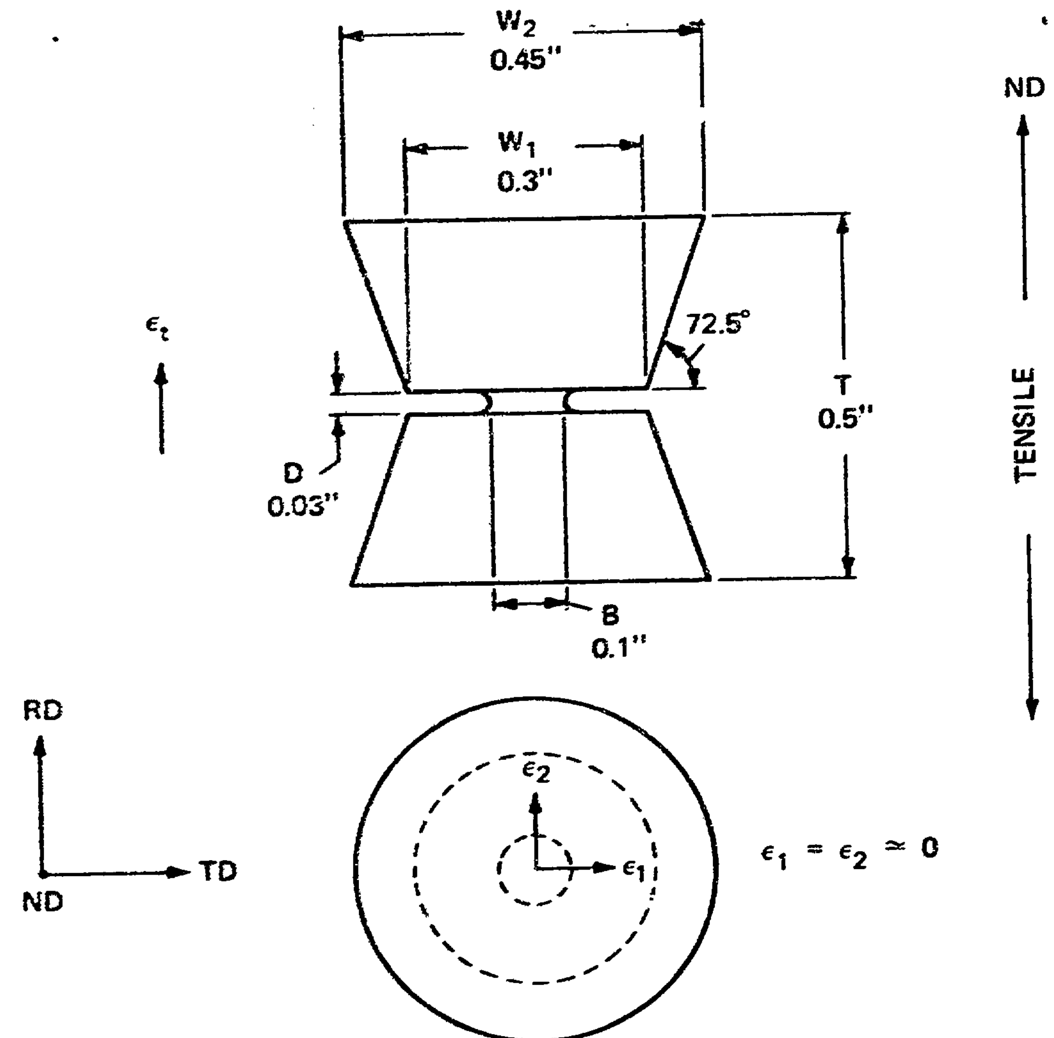
1"

Back

Ballistic-Tested Plate Having Nearly Random Texture.

P-5498B-5
P-5498D-6

Figure 14



(B = W/3, D = B/3.3, B = T/5)

SCALE 4:1

1 inch = 25.4 mm

THROUGH-THICKNESS NOTCHED TENSILE SPECIMEN FOR TESTING SPALLING RESISTANCE OF PLATE (STRAIN RATE CONSTANT)

DISTRIBUTION LIST

No. of Copies	To
1	Office of the Director, Defense Research and Engineering, The Pentagon, Washington, D. C. 20301
12	Commander, Defense Documentation Center, Cameron Station, Building 5, 5010 Duke Street, Alexandria, Virginia 22314
1	Metals and Ceramics Information Center, Battelle Memorial Institute, 505 King Avenue, Columbus, Ohio 43201
1	Chemical Propulsion Information Agency, Applied Physics Laboratory, The Johns Hopkins University, 8621 Georgia Avenue, Silver Spring, Maryland 20910
	Chief of Research and Development, Department of the Army, Washington, D. C. 20310
2	ATTN: Physical and Engineering Sciences Division
	Commander, Army Research Office, P. O. Box 12211, Research Triangle Park, North Carolina 27709
1	ATTN: Information Processing Office
	Commander, U. S. Army Materiel Development and Readiness Command, 5001 Eisenhower Avenue, Alexandria, Virginia 22333
1	ATTN: DRCDE-L, Light Armor Coordination Office
1	DRCDE-TC
1	DRCSA-S, Dr. R. B. Dillaway, Chief Scientist
	Commander, U. S. Army Electronics Command, Fort Monmouth, New Jersey 07703
1	ATTN: DRSEL-GG-DD
1	DRSEL-GG-DM
	Commander U. S. Army Missile Command, Redstone Arsenal, Alabama 35809
1	ATTN: Technical Library
1	DRSMI-RKK, Mr. C. Martens, Bldg. 7120
1	DRSMI-RSM, Mr. E. J. Wheelahan
	Commander, U. S. Army Armament Command, Rock Island, Illinois 61201
2	ATTN: Technical Library
1	AMSAR-SC, Dr. C. M. Hudson
1	AMSAR-PPW-PB, Mr. Francis X. Walter
	Commander, U. S. Army Natick Research and Development Command, Natick, Massachusetts 01760
1	ATTN: Technical Library

No. of Copies	To
	Commander, U. S. Army Satellite Communications Agency, Fort Monmouth, New Jersey 07703
1	ATTN: Technical Document Center
	Commander, U. S. Army Tank-Automotive Development Center, Warren, Michigan 48090
1	ATTN: DRDTA-R
2	DRDTA, Research Library Branch
	Commander, White Sands Missile Range, New Mexico 88002
1	ATTN: STEWS-WS-VT
	Commander, Aberdeen Proving Ground, Maryland 21005
1	ATTN: STEAP-TL, Bldg. 305
	President, Airborne, Electronics and Special Warfare Board, Fort Bragg, North Carolina 28307
1	ATTN: Library
	Commander, Dugway Proving Ground, Dugway, Utah 84022
1	ATTN: Technical Library, Technical Information Division
	Commander, Edgewood Arsenal, Aberdeen Proving Ground, Maryland 21010
1	ATTN: Mr. F. E. Thompson, Dir. of Eng. & Ind. Serv., Chem-Mun Br
	Commander, Frankford Arsenal, Philadelphia, Pennsylvania 19137
1	ATTN: Library, H1300, Bl. 51-2
1	SARFA-L300, Mr. J. Corrie
	Commander, Harry Diamond Laboratories, 2800 Powder Mill Road, Adelphi, Maryland 20783
1	ATTN: Technical Information Office
	Commander, Picatinny Arsenal, Dover, New Jersey 07801
1	ATTN: SARPA-RT-S
	Commander, Redstone Scientific Information Center, U. S. Army Missile Command, Redstone Arsenal, Alabama 35809
4	ATTN: DRSMI-RBLD, Document Section
	Commander, Watervliet Arsenal, Watervliet, New York 12189
1	ATTN: SARWV-RDT, Technical Information Services Office
	Commander, U. S. Army Foreign Science and Technology Center, 220 7th Street, N. E., Charlottesville, Virginia 22901
1	ATTN: DRXST-SD3

No. of Copies	To
	Commander, U. S. Army Engineer School, Fort Belvoir, Virginia 22060
1	ATTN: Library
	Naval Research Laboratory, Washington, D. C. 20375
1	ATTN: Dr. J. M. Krafft - Code 8430
2	Dr. G. R. Yoder - Code 6382
	Chief of Naval Research, Arlington, Virginia 22217
1	ATTN: Code 471
	Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio 45433
2	ATTN: AFML/MXE/E. Morrissey
1	AFML/LC
1	AFML/LLP/D. M. Forney, Jr.
1	AFML/MBC/Mr. Stanley Schulman
	National Aeronautics and Space Administration, Washington, D. C. 20546
1	ATTN: Mr. B. G. Achhammer
1	Mr. G. C. Deutsch - Code RR-1
	National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, Alabama 35812
1	ATTN: R-P&VE-M, R. J. Schwinghamer
1	S&E-ME-MM, Mr. W. A. Wilson, Building 4720
1	Ship Research Committee, Maritime Transportation Research Board, National Research Council, 2101 Constitution Ave., N. W., Washington, D. C. 20418
1	U. S. Steel Corporation Research Laboratories, Monroeville, Pennsylvania 15164
	Director, Army Materials and Mechanics Research Center, Watertown, Massachusetts 02172
2	ATTN: DRXMR-PL
1	DRXMR-CT
1	DRXMR-AP
1	DRXMR-PR
1	DRXMR-XC

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER (18) AMMRC (19) CTR-76-22

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle) (6) Effect of Crystallographic Texture, Retained Austenite, and Austenite Grain Size on the Mechanical and Ballistic Properties of Steel Armor Plates.

5. TYPE OF REPORT & PERIOD COVERED: Final Report July 1,1975-June 30,1976

6. PERFORMING ORG. REPORT NUMBER (14) 76-H-018

7. AUTHOR(s) (10) Hsun Hu, G. R. Speich, and R. L. Miller

8. CONTRACT OR GRANT NUMBER(s) (15) DAAG46-75-C-0094 NEW

9. PERFORMING ORGANIZATION NAME AND ADDRESS

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: D/A Project: 1T162105 AH84; AMCMS Code: ~~612105.11.H8400~~; Agency Accession:

11. CONTROLLING OFFICE NAME AND ADDRESS

Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172

12. REPORT DATE (11) July 1976

13. NUMBER OF PAGES (12) 76p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report) Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

(9) Final technical rept. 1 Jul 75-30 Jun 76

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

(16) DA-1-T-162105-AH-84

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Armor; Steel armor; Armor plate; Austenite; Mechanical properties; Ballistics; Texture

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The ballistic performance of a medium-carbon 5Ni-Si-Cu-Mo-V steel processed to plates with various degrees of textures, various amounts of retained austenite, and various austenite grain sizes has been studied. Results show that, with 0.50 caliber projectiles and 0 degree obliquity, the V_{50} ballistic limit of nearly random-textured plates is around 2030 to 2100 fps (666 to 689 mps), at a hardness of about 53.5 to 54.5 Rc. For approximately →

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED 407 909

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

the same hardness and in-plane mechanical properties, the ballistic limit of strongly (112) + (111) textured plates increased with increasing texture intensity. A ballistic limit of about 2360 fps (774 mps) was observed for the strongest texture produced in plates rolled 80 to 90 percent at 1500°F (815°C) before quenching. With this increased ballistic limit, the tendency for spalling also increased. At a constant strain rate, the spalling resistance appears to correlate qualitatively with the through-thickness notched tensile strength. Tempering quenched plates with a random texture at various high temperatures (1100 to 1300°F or 593 to 704°C) to vary the retained-austenite contents greatly reduced the ballistic limit, primarily because of the lowered hardness. For this range of low hardness and low ballistic limit, the latter increased with increasing retained-austenite contents, but with decreasing hardness. There was little difference in the ballistic limit of random-textured plates heat-treated to various austenite grain sizes prior to quenching. The ballistic properties of the plates and their correlations with texture, microstructure, and the through-thickness notched tensile properties are discussed.

AD ____________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
EFFECT OF CRYSTALLOGRAPHIC TEXTURE, RETAINED AUSTENITE, AND AUSTENITE GRAIN SIZE ON THE MECHANICAL AND BALLISTIC PROPERTIES OF STEEL ARMOR PLATES -
Hsun Hu, Gilbert R. Speich, and Robert L. Miller

Final Technical Report AMMRC CTR 76-22, July 1976,
76 pp - illus, DAAG Project 46-75-C-0094
AMCMS Code 612105.11.H8400, Unclassified Report

The ballistic performance of a medium-carbon 5Ni-Si-Cu-Mo-V steel processed to plates with various degrees of textures, various amounts of retained austenite, and various austenite grain sizes has been studied. Results show that, with 0.50 caliber projectiles and 0 degree obliquity, the V_{50} ballistic limit of nearly random-textured plates is around 2030 to 2100 fps (666 to 689 mps), at a hardness of about 53.5 to 54.5 R_C. For approximately the same hardness and in-plane mechanical properties, the ballistic limit of strongly (112) + (111) textured plates increased with increasing texture intensity. A ballistic limit of about 2360 fps (774 mps) was observed for the strongest texture produced in plates rolled 80 to 90 percent at 1500°F (815°C) before quenching. With this increased ballistic limit, the tendency for spalling also increased. Tempering quenched plates with a random texture at various high temperatures (1100 to 1300°F or 593 to 704°C) to vary the retained-austenite contents greatly reduced the ballistic limit, primarily because of the lowered hardness. There was little difference in the ballistic limit of random-textured plates heat-treated to various austenite grain sizes prior to quenching.

UNLIMITED DISTRIBUTION

Key Words

1. Ballistic properties
2. Steel armor
3. Thermomechanical treatment
4. Preferred orientation
5. Retained austenite
6. Texture

I. Hu, Hsun
II. Speich, G. R.
III. Miller, R. L.
IV. Contract DAAG46-75-C-0094
V. AMCMS Code 612105.11.H8400

AD ____________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
EFFECT OF CRYSTALLOGRAPHIC TEXTURE, RETAINED AUSTENITE, AND AUSTENITE GRAIN SIZE ON THE MECHANICAL AND BALLISTIC PROPERTIES OF STEEL ARMOR PLATES -
Hsun Hu, Gilbert R. Speich, and Robert L. Miller

Final Technical Report AMMRC CTR 76-22, July 1976,
76 pp - illus, DAAG Project 46-75-C-0094
AMCMS Code 612105.11.H8400, Unclassified Report

The ballistic performance of a medium-carbon 5Ni-Si-Cu-Mo-V steel processed to plates with various degrees of textures, various amounts of retained austenite, and various austenite grain sizes has been studied. Results show that, with 0.50 caliber projectiles and 0 degree obliquity, the V_{50} ballistic limit of nearly random-textured plates is around 2030 to 2100 fps (666 to 689 mps), at a hardness of about 53.5 to 54.5 R_C. For approximately the same hardness and in-plane mechanical properties, the ballistic limit of strongly (112) + (111) textured plates increased with increasing texture intensity. A ballistic limit of about 2360 fps (774 mps) was observed for the strongest texture produced in plates rolled 80 to 90 percent at 1500°F (815°C) before quenching. With this increased ballistic limit, the tendency for spalling also increased. Tempering quenched plates with a random texture at various high temperatures (1100 to 1300°F or 593 to 704°C) to vary the retained-austenite contents greatly reduced the ballistic limit, primarily because of the lowered hardness. There was little difference in the ballistic limit of random-textured plates heat-treated to various austenite grain sizes prior to quenching.

UNLIMITED DISTRIBUTION

Key Words

1. Ballistic properties
2. Steel armor
3. Thermomechanical treatment
4. Preferred orientation
5. Retained austenite
6. Texture

I. Hu, Hsun
II. Speich, G. R.
III. Miller, R. L.
IV. Contract DAAG46-75-C-0094
V. AMCMS Code 612105.11.H8400

AD ____________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
EFFECT OF CRYSTALLOGRAPHIC TEXTURE, RETAINED AUSTENITE, AND AUSTENITE GRAIN SIZE ON THE MECHANICAL AND BALLISTIC PROPERTIES OF STEEL ARMOR PLATES -
Hsun Hu, Gilbert R. Speich, and Robert L. Miller

Final Technical Report AMMRC CTR 76-22, July 1976,
76 pp - illus, DAAG Project 46-75-C-0094
AMCMS Code 612105.11.H8400, Unclassified Report

The ballistic performance of a medium-carbon 5Ni-Si-Cu-Mo-V steel processed to plates with various degrees of textures, various amounts of retained austenite, and various austenite grain sizes has been studied. Results show that, with 0.50 caliber projectiles and 0 degree obliquity, the V_{50} ballistic limit of nearly random-textured plates is around 2030 to 2100 fps (666 to 689 mps), at a hardness of about 53.5 to 54.5 R_C. For approximately the same hardness and in-plane mechanical properties, the ballistic limit of strongly (112) + (111) textured plates increased with increasing texture intensity. A ballistic limit of about 2360 fps (774 mps) was observed for the strongest texture produced in plates rolled 80 to 90 percent at 1500°F (815°C) before quenching. With this increased ballistic limit, the tendency for spalling also increased. Tempering quenched plates with a random texture at various high temperatures (1100 to 1300°F or 593 to 704°C) to vary the retained-austenite contents greatly reduced the ballistic limit, primarily because of the lowered hardness. There was little difference in the ballistic limit of random-textured plates heat-treated to various austenite grain sizes prior to quenching.

UNLIMITED DISTRIBUTION

Key Words

1. Ballistic properties
2. Steel armor
3. Thermomechanical treatment
4. Preferred orientation
5. Retained austenite
6. Texture

I. Hu, Hsun
II. Speich, G. R.
III. Miller, R. L.
IV. Contract DAAG46-75-C-0094
V. AMCMS Code 612105.11.H8400

AD ____________

UNCLASSIFIED
UNLIMITED DISTRIBUTION

Army Materials and Mechanics Research Center,
Watertown, Massachusetts 02172
EFFECT OF CRYSTALLOGRAPHIC TEXTURE, RETAINED AUSTENITE, AND AUSTENITE GRAIN SIZE ON THE MECHANICAL AND BALLISTIC PROPERTIES OF STEEL ARMOR PLATES -
Hsun Hu, Gilbert R. Speich, and Robert L. Miller

Final Technical Report AMMRC CTR 76-22, July 1976,
76 pp - illus, DAAG Project 46-75-C-0094
AMCMS Code 612105.11.H8400, Unclassified Report

The ballistic performance of a medium-carbon 5Ni-Si-Cu-Mo-V steel processed to plates with various degrees of textures, various amounts of retained austenite, and various austenite grain sizes has been studied. Results show that, with 0.50 caliber projectiles and 0 degree obliquity, the V_{50} ballistic limit of nearly random-textured plates is around 2030 to 2100 fps (666 to 689 mps), at a hardness of about 53.5 to 54.5 R_C. For approximately the same hardness and in-plane mechanical properties, the ballistic limit of strongly (112) + (111) textured plates increased with increasing texture intensity. A ballistic limit of about 2360 fps (774 mps) was observed for the strongest texture produced in plates rolled 80 to 90 percent at 1500°F (815°C) before quenching. With this increased ballistic limit, the tendency for spalling also increased. Tempering quenched plates with a random texture at various high temperatures (1100 to 1300°F or 593 to 704°C) to vary the retained-austenite contents greatly reduced the ballistic limit, primarily because of the lowered hardness. There was little difference in the ballistic limit of random-textured plates heat-treated to various austenite grain sizes prior to quenching.

UNLIMITED DISTRIBUTION

Key Words

1. Ballistic properties
2. Steel armor
3. Thermomechanical treatment
4. Preferred orientation
5. Retained austenite
6. Texture

I. Hu, Hsun
II. Speich, G. R.
III. Miller, R. L.
IV. Contract DAAG46-75-C-0094
V. AMCMS Code 612105.11.H8400